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Interactive Brooches: Physical Interfaces on Smart Textiles

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Abstract

Recently, smart textiles gained more attention in research and industry because they enable new unobtrusive ways of human-computer interaction. Google's Advanced Technology and Projects group (ATAP) already demonstrated that conductive yarn can be incorporated into fabrics using standard weaving technology. While there exists work that combines smart textiles with 3D printing, the use of conductive filament as a complementary material that can add dimension and movement has not been explored already. This work describes the design and implementation of 3D-printed brooches and places them in a design space for Interactive Brooches. Additionally, we describe a technique to connect the brooches to a circuit board on the fabric. Finally, we conduct an exploratory study to validate the requirements and acceptability of our designs.

Überblick

In letzter Zeit haben intelligente Textilien in Forschung und Industrie mehr Aufmerksamkeit erlangt, weil sie neue, unauffällige Wege der Mensch-Computer-Interaktion ermöglichen. Google's Advanced Technology and Projects Group (ATAP) hat bereits gezeigt, dass leitfähiges Garn mit Hilfe von Standard Webtechnologien in Stoffe eingearbeitet werden kann. Während es Arbeiten gibt, die intelligente Textilien mit 3D-Druck kombinieren, ist die Verwendung von leitfähigem Filament als zusätzliches Material, welches Dimension und Bewegung hinzufügen kann, noch nicht erforscht. Diese Arbeit beschreibt das Design und die Implementierung von 3D gedruckten Broschen und platziert sie in einem Designraum für Interaktive Broschen. Zusätzlich wird eine Technik beschrieben, um die Broschen mit einer Leiterplatte auf dem Stoff zu verbinden. Abschließend führen wir eine explorative Studie durch, um die Anforderungen und die Akzeptanz unserer Entwürfe zu überprüfen.

Chapter 1

Introduction

Recently smart textiles gained more attention in research and industry because they enable new unobtrusive ways of human-computer interaction. At the heart of smart textiles is conductive yarn. A few years ago, Google's Advanced Technology and Projects group (ATAP) demonstrated that conductive yarn can be incorporated into fabrics using a standard weaving technology (Poupyrev et al. [2016]).

In order to make garments with embedded conductive yarn smart, one has to connect the yarn to some kind of computer. This connection is a critical part for manufacturing because soft flexible yarn must be attached to rigid electronic components.
Besides clipping, stitching or soldering (Brauner et al. [2017], Linz et al. [2008], Poupyrev et al. [2016]) the use of 3D-printed conductive polyester has been explored for this connection. Grimmelsmann et al. [2016] have demonstrated that small printed sockets improve the connection between conductive textiles and tiny SMD-LEDs.

However 3D printing with conductive filament brings even more possibilities than just printing sockets. One can print various objects that can add dimension, texture, and functionality to fabrics, similar to textile embellishments. Textile embellishments are external media such as zippers, buttons, sequins, and brooches that are added to fabric for expressive and/or functional purposes. Traditional embellishment techniques include printing, laminating, stenciling, sewing, embroidering, bonding, etc. 3D Systems[1] developed a 3D printer, named Cube, that prints three-dimensional models directly on fabric as a way of embellishment. But until now the use of conductive filament has not been explored as a complementary material that can add dimension and movement to conductive yarn-based smart textiles.

In this thesis, we present Interactive Brooches, 3D objects that are printed using conductive and non-conductive filament and attached to smart textiles to create dynamic physical interfaces. We present the design and fabrication pipeline of Interactive Brooches using conductive polyester. Additionally, we describe a technique to connect the Brooches to a circuit board on the fabric. Four example Brooches are presented and placed in a design space for Interactive Brooches. Finally, we conduct an exploratory study to validate the requirements and acceptability of our designs in a qualitative user study with ten participants.

This work is structured as follows: In Chapter 2 an overview of smart textiles in general is given and linked to the addition of conductive filament. The fabrication process of four Interactive Brooches and the interaction design is presented in Chapter 3. After that, different aspects of our implementation are explained in Chapter 4. To evaluate the design and implementation we conduct an exploratory user study, the results of which are discussed in Chapter 5. Finally, in Chapter 6 we conclude the thesis and look into limitations and what is future work.

[1]https://www.3dsystems.com/press-releases/3d-systems-introduces-fabricate-3d-printing-directly-textiles-cube-3d-printer

Chapter 2

Related Work

2.1 On-Body Interaction

Wearable electronic devices have become a common part of our life. But still mobile devices rely on screens as primary input modalities. By adding the pericutaneous space, the space immediately outside the body, the interaction area can be expanded while remaining easily accessible. Researchers already explored the skin as an area of interest. Weigel et al. [2015] proposed skin-worn sensors for touch input on the body. These on body interactions are greatly improved by the kinesthetic sense: The awareness of parts of our body's position with respect to itself (Tan et al. [2002]). Additionally to the kinesthetic sense, recognizable landmarks of the skeletal structure or the variations in skin texture were considered by Weigel et al. [2017]. They showed how spatial cues of these landmarks help in guiding input on the body and allow for easy recall of mappings. However, people wear clothes thus the interaction area does hardly increase if one adds skin, because often the accessible skin area is limited to just the hands and face. Therefore, textiles moved into the field of interests of researchers.

kinesthetic sense improves on-body interactions

2.2 Conductive thread based Interfaces

Currently most research on touch-sensitive textiles, or smart textiles, contains the two basic elements fabric and conductive yarn. Researchers integrate conductive yarn into clothing as capacitive touch sensors (Rekimoto [2001]) or pressure sensors (Sergio et al. [2002]). Smart textiles enable invisible, ubiquitous interactivity and are easy to manufacture. Poupyrev et al. [2016] proposed an inexpensive technique using standard weaving technology in order to produce interactive textiles at scale. They presented a work flow starting with manufacturing yarn up to weaving textiles to use in consumer garments.
Touch-sensitive textiles add the properties of textiles to touchscreens: flexibility, stretchablility, lightness, multiple textures and low cost of textile production. Gilliland et al. [2010] presented a swatchbook: A collection of GUI-like widgets made with conductive embroidery with the addition of using tactile features to improve the usability of the interfaces. Having tactile features is one more advantage towards touchscreens and is emphasized by many researchers of smart textiles (Parzer et al. [2017], Poupyrev et al. [2016]). Brauner et al. [2017] took the haptic support of textiles one step further and created input devices by folding the fabric and sewing pleats. They also mentioned the limits of using flat textured surfaces and considered expanding the interfaces into three-dimensional structures using 3D mashes or weaving in 3D.

tactile features improve usability

In order to expand the interaction capabilities of smart textiles, accessories were considered, too. Schwarz et al. [2010] investigated the input capabilities of cords as intuitive, high-accuracy, multi-degree-of-freedom input method. Also, the use of belts (Dobbelstein et al. [2015]) or pockets (Dobbelstein et al. [2017]) as input devices were explored. For all of these three input devices the benefit of spatial mapping and the unobtrusive interaction is emphasized. Dobbelstein et al. additionally presented a user study to show that people perceive these new input capabilities as socially acceptable in public.

Perner-Wilson et al. [2011] created a construction kit to build textile interfaces like a tilt sensor with a free-swinging metal bead or a fur shawl with integrated stroke sensors. These embellishments that are added to basic garments come with physical affordances and unique tactile features. As most embellishments have moving parts, this thesis analyzes using moving parts of embellishments as input interfaces.

2.3 Conductive filament based Interfaces

While there are many types of 3D printing, the most affordable and therefore the most prolific today, is Fused Deposition Modeling (FDM). Rapid prototyping with FDM printers had its breakthrough in 2011 when Jones et al. [2011] presented RepRap, a low cost replicating 3D printer. FDM printers build the object by stacking thin layers of thermoplastic coming from a filament roll (Zein et al. [2002]). The filament is melted by a heated nozzle at a temperature of around 220 degrees Celsius and then is extruded on top of a build platform. When cooling down the thermoplastic solidifies in seconds and adheres to the platform or the already printed layers. After each layer is printed the nozzle moves up several hundred micrometers and continues the print with the next layer.

3D printing conductive polyester

Today the most common used thermoplastic is polylactic acid (PLA), but already in 2012 the use of conductive composite material for 3D printing was explored. Leigh et al. [2012] presented formulation of a "simple conductive thermoplastic composite" and demonstrated the use in capacitive sensors or printed circuits. In order to be conductive a conductor has to be added to the filament. While Leigh et al. [2012] used carbon black as low-cost conductive filler there also exists metal-ion based filament with silver ions as filler. The advantage of significantly lower electrical resistivity than carbon based filament comes with the disadvantage of vastly shorter shelf life due to higher sensitivity for UV irradiation and thermal or electrical stress (Kwok et al. [2017]). The most commercially available filaments are graphene-based composites based on PLA because of their ease of use and lower cost than metal-based filament.

Table 2.1 shows an overview of the most prolific conductive filaments and puts the price in relation to the resistivity.

Grimmelsmann et al. [2016] used conductive filament as an interface between small electronic components and textiles and utilized 3D printing to connect SMD-LEDs to smart textiles. This thesis investigates if there is a way to use conductive filament in order to create smart embellishments like brooches that provide new possibilities of interaction.

manufacturer	conductor	price per 100g	resistivity
Electrify	silver ions	160 €	0.01 Ωcm
BlackMagic3D	carbon black	90 €	0.6 Ωcm
Proto-Pasta	graphene	6 €	6 Ωcm

Table 2.1: Most common conductive filaments listed with price and resistivity

Chapter 3

Design and Interaction

In the following Chapter we present Interactive Brooches and describe their design process in detail. After that, the functionalities of these brooches are placed in a design space for Interactive Brooches.

3.1 Design of Four Interactive Brooches

We present four Interactive Brooches: a circular button, a blossom, a springy brooch and an eagle. All brooches were 3D-printed with both conductive and insulating filament, except for the button in Figure 3.1a which is solid metal. Choosing a metal button has the benefit of using another surface texture while still providing electrical conductivity. There are already 3D printers that are able to print other materials than polyester, therefore the button could be printed to the depicted form as well.

3.1.1 Circular Button

The raise on the side of the circular button (Figure 3.1 a), together with its overall design appeal to stroke it in circular movements. Inspired by this affordance the button

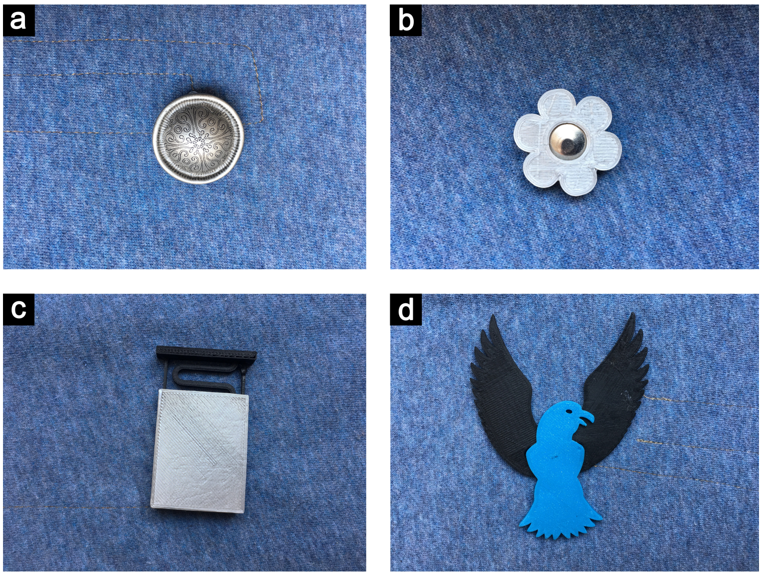

Figure 3.1: Four functional brooches used in the study

was sewed onto the textile with conductive yarn. To detect the direction of movement, the textile was equipped with two contact points. Then the button was connected to 5V main of an Arduino interface board and the two contact points were connected to input pins with a pull-up resistor to ground. Caused by the raise for its sewing hole the button is always touching the fabric on one side. If it touches one of the two contact points the circuit is closed and the respective input pin measures voltage.

measuring direction of rotation

With a short program loaded onto the Arduino it is now possible to detect whether one rotates the button clockwise or counter clockwise. The direction of rotation is measured between touching intervals at the contact points. As depicted in Figure 3.2 the button is being turned clockwise, if the time t_1 between touching the two contact points starting at the top is short and the next time frame t_2 is longer than the first. Otherwise, if the first time frame is longer than the second time frame, the button is being turned counter clockwise. In addition to the rotation direction the time for an entire circle could be used to calculate the duration of the interaction.

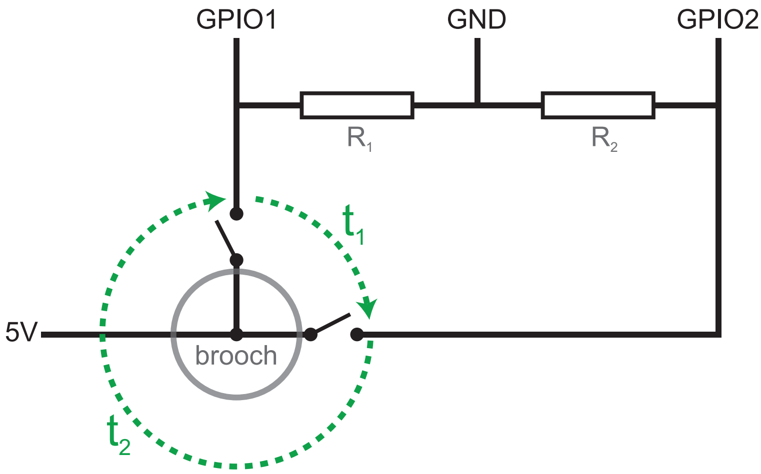

Figure 3.2: Wiring schematic for circular button with time frames to calculate rotation direction

3.1.2 Blossom

The flower in Figure 3.1b can be manipulated in a similar way. Rotation direction and rotation duration can be measured in a very similar way like described above. Due to the fact, that the blossom is flat it does not tilt and therefore will not make contact with one point respectively. The rotating petals can be used as make and break switch for the circuit. This makes it necessary to print the blossom with conductive filament. After printing, the blossom was connected to a metal snap fastener in order to make electrical contact with the fabric. Due to its redundant function the blossom was not connected to the Arduino but still included in the set of brooches to provide another tactile design for a turning button.

3.1.3 Springy Brooch

In order to expand the haptic feedback a springy brooch as depicted in Figure 3.1c was printed. It is made out of a fully conductive 3D-printed spring in addition to a protecting case made out of insulating material. The spring is also guided with a rail on each side to improve the sturdiness.

The spring has a resilient feel to it, because conductive filament is more flexible than common PLA filament. In contrast to the other brooches the spring works with only one electrical wire. For this reason a metal safety pin was chosen as attach mechanism and tt was attached to a little contact point made out of conductive yarn to make electrical contact with the smart fabric. The safety pin provides a fast and reliable way for attaching the brooch.

using capactivie sensing to detect interaction

In order to make an interface device the Arduino CapSense[1] code library was used. The CapSense library uses two IO pins on the Arduino interface board and turns one pin into a capacitive sensor to sense the electrical capacitance of the human body. The sensor requires just a single high value resistor and a conducting sensing pad, in our case the 3D-printed spring. Figure 3.3 shows the used circuit. When the send pin changes state, it causes a change in state of the second connected pin, the receive pin. The delay between the change in state of the send- and the receive pin is determined by the value of the resistor multiplied by the capacitance at the receive pin, including any other capacitance connected to it. For the explained use case this means, that the capacitance at the receive pin is higher, as soon as a user touches the conductive part of the spring. In addition it is possible to measure how hard the user presses the spring. This is due to two factors: First, when being pressed down, the user presses harder on the conductive surface, therefore the contact area and with it the capacitance increases. Second, when being flexed, the resistance of conductive filament and thus the capacitance increases (Leigh et al. [2012]).

3.1.4 Eagle

Inspired by existing non-smart brooches a more vivid one was designed. The idea was to have an animal with natural moving parts (e.g. tails, wings, legs) which will be used as an input interface. The eagle (Figure 3.1d) has two wings that are attached to its body and can be moved up and down. Before printing, the fabric was equipped with

[1] https://playground.Arduino.cc/Main/CapacitiveSensor

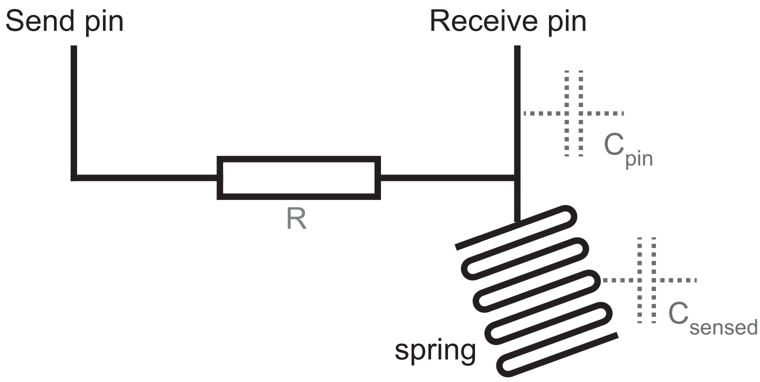

Figure 3.3: Circuit used with CapSense to detect capacitance of a user

three contact points. Afterwards, the blue part was directly printed onto the fabric, followed by the two wings which were seperatly printed with conductive filament and later attached to the body.The current prototype only allows the interaction in moving the right wing. Again the circuit is very similar to the round button and the blossom: One contact point provides 5V main, the other two act as a switch. They connected to an input pin of the Arduino interface board and to ground with a pull-up resistor. With this simple circuit it is possible to detect three different states for the wing: bottom, middle and top.

3.2 Interaction Design

The described techniques allow a wide range of interactions. An overview of the input modalities designed for this thesis is depicted in Figure 3.4. For linear motion and circular motion respectivly, three increments of input types are listed. The depicted models describe example designs for these types. The parts depicted in grey or black should be printed with conductive filament, in order to work as intended.

The binary value, indicating whether the user touches a brooch can be implemented with the earlier described

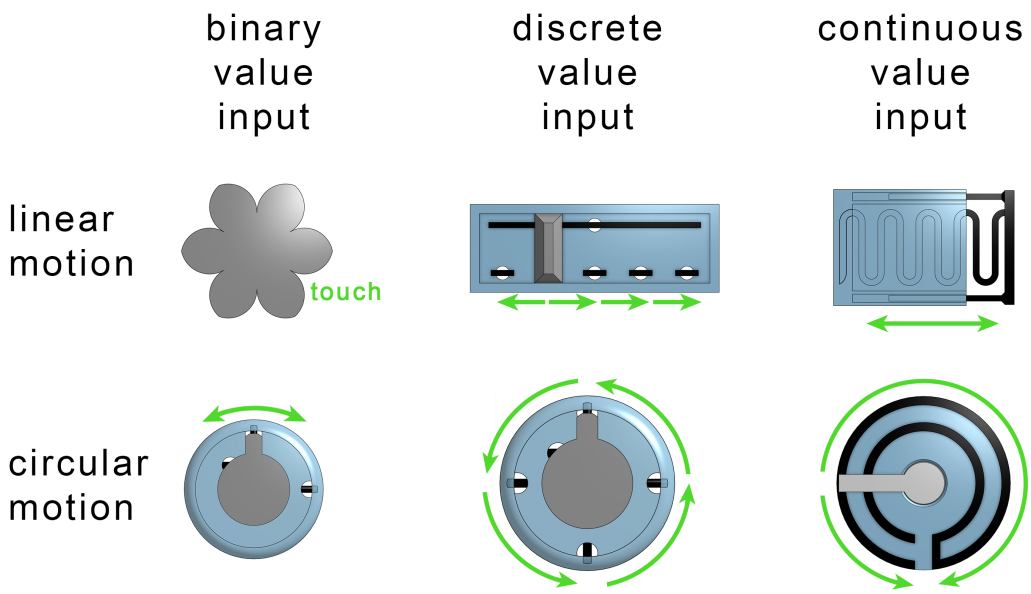

Figure 3.4: overview of possible input values in different direction of motion

CapSense technology (Figure 3.3). Determining the direction of rotation is also presented earlier and depicted in Figure 3.2.

The two examples for discrete input value in linear and circular motion is implemented straight forward: Both have a slider that is always connected to 5V current and contact points connected to input pins of the Arduino interface board with a pullup resistor to ground. The pullup resistor is necessary to allow the functionality of a simple button. If the slider makes contact with one of these points the circuit is closed and the state of the respective pin changes. With the described technique it is possible to distinguish between four different states with the turning knob. The presented slider even enables five different states.

The continuous value input for linear motion is described in detail in the previous Section 3.2 "Interaction Design" and depicted in Figure 3.3. As the common conception of volume knobs are circular turning knobs we also tried to detect circular motion with continuous values. The used technique is directly inspired by mechanical potentiometers. These consist of a high resistance element (black traces) and a sliding contact that moves along the element (grey wiper). Theoretically, by measuring the resistance of the circuit it is possible to map the resistance to the angle of the wiper, but the printed example did not work as expected. While it was possible to change in resistance, the fluctuations were too high to reliably map it to the angle of the wiper. The problem was reasoned with two factors: First, the wiper does not always make the same contact at all points and therefore the contact resistance differs when rotating it. Second, the brooch was only printed with one type of conductive filament and therefore the difference in resistance of the wiper and the black traces is not high enough to get reliable resistance deltas while turning.

continuous circular value input hard to measure

Chapter 4

Implementation

In this Chapter different aspects of the fabrication are presented. An important issue is the attachment mechanism which predetermines the usability of the brooches. Therefore the implementation of three techniques are presented. Ultimately, a novel 3D-printed interface is presented to include circuit boards into the smart brooches.

4.1 Fabrication

3D printing has the ability to create prototypes easily and cheap. This technology therefore is ideal for the evaluation of brooches with different tactile features. Additionally it is easy to iterate during the design process. The production of a prototype consists of the following three steps: The design of a 3D model using CAD software, the application of printer- and filament specific parameters and the final printing on a 3D printer. We will take a closer look on each step in the following sections.

The 3D models were created with the online computer-aided design (CAD) tool *Onshape*[1]. Onshape is a cloud computing system that provides a free CAD system for college students and educators via a Software as a Service model.

[1]https://www.onshape.com

The finished 3D model was exported as .stl (abbrevation of stereolithography) file. The stl file format describes the surface geometry of three-dimensional objects and hence is widely used for rapid prototyping and 3D printing. It describes the raw, unstructured triangulated surface by the normal and the vertices of the triangles.

preparing models for printing with conductive filament

The stl file was then imported to the free software *Ultimaker Cura*[2]. Cura prepares 3D models for printing. In this software printer-specific and filament-specific settings are adjusted. There are mainly two properties, that have to be adjusted in the process of printing conductive prototypes: The speed of printing and the infill. In order to improve conductivity, the conductive filament is printed with a speed of around 30mm/s which is around two thirds of the speed regular PLA filament is printed. The more important factor for excellent conductivity is the infill. Objects are rarely printed as solid parts. Instead they are printed with a solid shell and sparse infill. How dense this infill honeycomb is printed is determined by the infill density. While regular prints are often printed with an infill density of around 20%, the conductive parts were printed with an infill density of 100%. This ensures maximal linkage between the printed traces not only at the shell, but in the entire solid part and hence maximizes electronic conductivity inside the part. When all options are set, the software converts the object together with the settings into G-code[3]. G-code is a numerical control programming language, which characterizes a 3D object as a series of machine commands. In our case the G-code file contains the coordinates the printer has to move to for every layer in addition to the information for the motor that extrudes the filament. Finally the file is loaded onto the printer and the object is printed. In our case the print of a brooch took about 15 minutes.

Prototype brooches were iterated over several weeks exploring different designs. In addition to printing, other conductive accessories like metal ornament buttons or studs were considered too. As studs are easy to attach and often made out of conductive material, they work great as a simple conductive button on smart fabric. But as this thesis

[2]https://ultimaker.com/en/products/ultimaker-cura-software
[3]https://en.wikipedia.org/wiki/G-code

focuses on brooches with moving parts and haptic feedback studs were viewed as too limited.

4.2 Attachment Techniques

In the following Section several attachment techniques for smart brooches are described. Some are known techniques, for example sewing on a button, but new techniques like printing directly on fabric are also considered. In order to be smart the connections do not only have to hold well, but also serve as electric conductor between the smart brooch and the conductive yarn.

4.2.1 Sewing

The most obvious approach when attaching smart brooches to garments is to look at attachment techniques for already existing embellishments and buttons. As the common way to fasten buttons on fabric are sewing holes, these were added to the first prototypes. Being easy to attach is the biggest advantage, with the drawback of being fixed definitely. As the goal for non-decorative brooches like buttons is to make them very small, the sewing holes should be small too. When printing sewing holes the properties of the used 3D printer have to be factored in during the design process. On the one hand the holes have to be printed with a small diameter and should still be solid enough prevent breaking, but on the other hand the holes have to be wide enough to fit a needle with yarn. Like most entry level 3D printers our printer (Geeetech Delta Rostock Mini G2S) has a nozzle diameter of 0.4 mm which aligns with the extruded filament width. In order to print shapes as small as possible one should use a multiple of the nozzle diameter. In our case the width of the holes and the width of the separator in between worked best with a value of 0.8 mm.

printing properties of small sewing holes

Different prototypes were printed with either sewing holes, that hide under a second component of the brooch or with visible sewing holes on the side. In order to function as

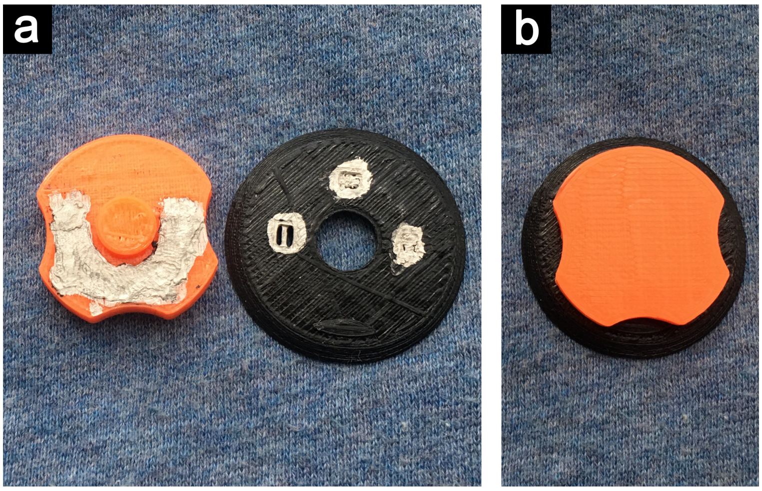

Figure 4.1: Early prototype with sewing holes using silver paint as conductor

electrical connection the sewing hole can be printed with conductive filament. In that case the conductive thread is fastened to the conductive material of the smart brooch.

using silver conductive paint in prototypes

The first prototypes were printed without conductive filament but silver conductive paint was added as depicted in Figure 4.1. The orange part of the knob clips into the black base and can be rotated. The base was sewed onto a sweater with conductive yarn and connected to a microcontroller to give it function. Then the three sewing holes and part of the orange clip were painted with silver paint (Figure 4.1a). With this turning knob four distinct states can be distinguished. In addition it has little tactile feedback, as the three indentations snap into a small hump at the lower side of the base. The indentations are affordances to grasp on. In the future, the silver paint can be replaced by printing with regular and conductive filament. This reduces manufacturing time and can be done in one step.

4.2.2 Printing on Fabric

Another way of adhering and making electrical contact would be to directly print the brooch, or parts of it, onto the

```
G1 Z15   ;move printhead to z=15 (x=0, y=0)
G92 Z13  ;treat current position as z=13
G0 Z0    ;move to new, adjusted Z0 position
```

Figure 4.2: Code to change the z-offset

fabric. Printing on fabric was already explored by Rivera et al. [2017] to create new opportunities for rapid prototyping with embedded flexibility. Additionally Grimmelsmann et al. [2016] already combined smart textiles with conductive filament to improve mechanical and electrical contacting.

In order to make electrical contact with the brooch the fabric has to be equipped with contact points made out of conductive yarn or conductive fabric. Having the preprocessed fabric ready, it has to be fastened on top of the bed of the 3D printer. Depending on the thickness of the fabric, the zero point for the height (z-axis) of the printer has to be adjusted. The difference between the standard zero point directly on top of the print bed and the now adjusted point is called z-offset. A z-offset of two millimetres was found to be best for the prototypes of this thesis but this varies depending on the thickness of the fabric used. At two millimetres z-offset the nozzle of the printer is still touching the fabric, which is desirable to make good contact with it. With some applications that parse G-code the user can define the offset in the graphical user interface, but it is also possible and likewise fast, to change it directly in the code. Therefore three lines of code were added to the start of the G-code as depicted in 4.2.

adjusting z-offset for printing on fabric

Due to the high temperature during the printing process, the filament fuses with the semi-synthetic fibers of the garment. The blue part of the bird in Figure 3.1 was printed directly onto the fabric. With this technique the brooch is permanently attached to the fabric and holds tight, but the fabric looses its flexibility in proximal space caused by the stiffness of the brooch.

Figure 4.3: Spring and flag with safety pins molten to the conductive part of the brooch

4.2.3 Pinning

Today brooches are often attached with a sharp pin, inserted directly through the fabric. Inspired by this technique, metal safety pins were used in two prototypes as depicted in Figure 4.3. In both cases the parts were printed with conductive filament (black) and insulating filament (grey), leaving a small hole for the head of the safety pin. When the print was finished the pin was heated with a soldering iron and pressed onto the brooch. Caused by the heat, the safety pins fuses with the filament and is attached permanently.

In order to function as a smart brooch the safety pin has to be attached to a conductive part on the fabric. With this technique the brooches are easy to attach and detach. The only drawback of the explained attachment method is the single contact point. Therefore the scope of applications is limited to conductive sensing explained earlier (see Figure 3.3).

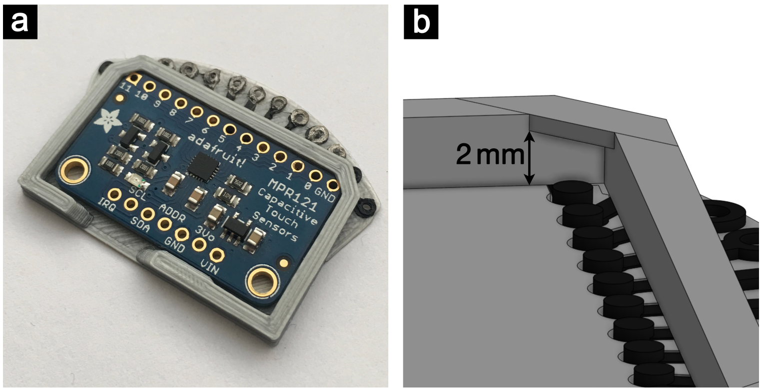

Figure 4.4: 3D-printed interface for an adafruit capacitive touch sensor board and closeup of CAD model

4.3 3D-printed Sockets

In order to make garments smart there has to be some kind of controller attached to the fabric. Today stiff electronic components like batteries or microprocessors are hard to integrate in a flexible circuit made with conductive yarn. Therefore researches have explored the use of staples or directly stitching in (Linz et al. [2008]) printed circuit boards (PCB) into the fabric. Brauner et al. [2017] present a clipping mechanism for making the connection between soft, flexible conductive yarn and stiff electronics.

printed socket with PCB clipping mechanism

A novel way of attaching PCBs to smart fabrics is presented in the following. With this interface it is possible to sew a small 3D-printed socket to the fabric, which can hold a PCB via a clipping mechanism. Sewing holes are printed with conductive filament on a thin base and the filament is then traced to the contact points of the board. In order to make electrical contact the board is firmly pressed onto the printed pins. For best electrical conductivity these contact points are printed one layer higher than the bottom of the socket. A working prototype is depicted in Figure 4.4a. The left picture shows the 3D-printed socket with an Adafruit capacitive touch sensor board[4]. Figure 4.4b shows a closeup of the CAD model. The used PCB is 1.7 mm thick

[4]https://www.adafruit.com/product/1982

and it was found that the board holds well when being pressed into a 2 mm high clip.

The benefit of the shown interface is the higher distance between the contact points. As Brauner et al. [2017] point out, the distance between signal lines made of conductive yarn should be at least 2.6 mm. The 3D-printed interface increases the distance from 2.5 mm to 3.5 mm and provides sewing holes with a diameter of 1.4 mm.

printing 3D circuit layouts

Additionally printing circuits with a 3D printer brings a broad range of possible interfaces between conductive yarn and PCBs. The presented interface is just a two-dimensional circuit board and was constructed to only increase the distance between the contact points but Kwok et al. [2017] demonstrated that 3D circuits can be printed as well. With this interface the controller of smart fabrics can be included inside a brooch that is only slightly bigger than the PCB. The brooch can then be sewn onto the garment and provides a fast and easy way of detaching the board.

Chapter 5

Exploratory Study

This Chapter presents the results of an exploratory user study using four example brooches to observe and analyse the requirements and usage for smart brooches.

5.1 Method

Today, there is no research available exploring the usability of interactive embellishments on e-textiles. While some researchers evaluated the use of accessories like belts as input devices (Dobbelstein et al. [2015]), the goal of this exploratory study was to get a better understanding of the acceptability of smart embellishments like brooches. As we are still in the development process, the study was conducted to capture the reactions of users early in the process to improve the design and give an understanding of the requirements.

aim

In a semi-structured interview ten participants were asked eleven questions that aimed to improve the understanding of needs, practices, concerns and preferences for smart brooches. The participants (6 male, 4 female) had an average age of 26 (range: 22 to 35) and seven of them had an academic background.

participants

procedure

The questions for the interview were structured in a way that gives the participants an opportunity to express their own ideas first, then to regard and to use prototypes in action and in the end to add thoughts or remarks. In case a participant already answered a later question when elaborating an earlier answer, questions were skipped or merged to improve the course of the interview. In some cases, questions were added to follow up on an idea or remark of a participant. Overall, the interviews took approximately 40 minutes. During the interview, a set of four example brooches was given to the participants, depicted in Figure 3.1. Their function was described and the participants had time to try them out on their own.

apparatus

The interviews took place at locations which the participants suggested, often choosing their own home. During the exploration the participants' hands were filmed with an iPhone 6S to have a record of the detailed interactions with the brooches. The rest of the interview was voice recorded and later transcribed. Additionally, short notes were written during the interview. The used interview protocol is attached as appendix A.

5.2 Discussion

When looking at the requirements regarding the user experience of brooches, there are many things a brooch should fulfill. The following Chapter will draw the line between general properties of an ordinary brooch and specific properties for smart brooches. Naturally, the importance of the properties differs from person to person it is possible to draw a rough order by means of the study.

Generally speaking, brooches should be *pleasant to look at*. This characteristic does not only apply to ordinary brooches but also to smart brooches. The user study shows that every participant mentioned at least the visual aesthetics. Some even said, the functionality does not matter if it does not look good. Regarding the aesthetics, the style of the brooch is also important. Some men were particularly critical and mentioned brooches like flowers or animals by itself were feminine. In common one could say, you wouldn't wear an ugly thing just for the functionality.

brooches provide superior tactile feedback

Narrowing the focus on requirements for smart brooches *tactile feedback* is very important. As described earlier in Chapter 2 "Related Work" providing tactile feedback is a central point of this work it was from the beginning on part of the motivation behind it. A brooch itself already provides more tactile feedback than smart fabrics. With fabrics the tactile feedback is limited to the texture of the fabric. Imagine having two buttons made of different types of cloth: One can distinguish them without looking by feeling the different surfaces. In addition to that, it is also possible to sew in pleads or to stitch elevated traces of yarn to create unique tangible surfaces.
On the other side, brooches attached to garments provide more tactile capabilities than fabric itself. Of course this is partly due to the addition of another material to the garment. It is easy to distinguish a button made of metal from a button made of denim fabric just by brushing the surface. Nevertheless, this is only a small part of the tactile feedback which makes smart brooches beneficial for user input. With brooches, or attachments in general, one can not only feel the different parts of it but also pull, push, turn and manipulate them in different ways depending on the object. For this work, brooches with moving parts and therefore even more tactile feedback were designed to improve eyes-free interaction and usability. In the user study, when asking for the preferred brooch, participants over all chose different ones but always argued with the type of tactile feedback their preferred brooch provided. The user experience has to be flawless in order to make the user want to wear such things.

Talking about user experience, the *applicability* is important, too. When we asked the participants about any problems of which they could think, the most frequent answer was false activation. This comes from natural thoughts: Today we wear garments as expedient objects and one does not watch out for not touching a specific point on the garment in fear of triggering a command. Adding smart fabric or brooches and therefore input capabilities comes along with the costs of higher awareness of your garments and the functions the different parts provide. This can partially be considered in the design process of the smart brooches but can not be fully prevented. A well designed brooch should have as little as possible false activations, so that the user does not care. The study showed that this threshold also differs from person to person. One participant said he would stop wearing something by the first false activation, while others said they would not care about rare accidental activations. In addition to that, the importance also varies with the command which is triggered. Generally speaking, the function should only be triggered if it is explicitly touched or exposed to direct force for example when bumping into a wall.

false activations need to be prevented

Being exposed to direct force should also not break the brooch. If people add an additional part of metal, plastic or even fabric to the garment, there is one more thing that can get caught on something, fall off when the user is doing sports or break when being exposed to too much force. Ideally, the smart brooch is robust but still easy to attach. In Chapter 4 "Implementation" different attachment techniques are described.
Not only being robust but also being waterproof is beneficial too. Forgetting the brooch on a garment and putting it in the washing machine should not brake it. Different types of weather have to be considered. In addition to rain and sweat, coldness and heat should not not affect the functionality of the smart brooch.

Being caught on something can directly be translated to the shape and size of the brooch. A small and round one, like a button or knob, is easier to handle than a big one like a bird with spread wings. One participant of the study imagined the brooches to be as small as possible but still have tactile feedback when using them. This does not mean that every brooch has to be very tiny but that they should come in different forms and sizes. As most people are selective with their garments or jewellery one can assume that smart brooches are selected likewise. A participant of the study explained she would mainly wear brooches with neutral colours but explicitly use loud colours as eyecatcher. Therefore, different materials and different colours should be considered.

5.3 Data Analysis

Overall, the participants were open-minded to the presented ideas. As the requirements for brooches are already explained in the previous Section, the following evaluation concentrates on the usage of Interactive Brooches. When exploring the given brooches, four participants were vocally impressed by their functionality. When being asked, if they would wear some kind of smart brooch, every participant affirmed the question. Some explicitly mentioned that they would only wear something that looks nice and two participants said the brooch must not look like an input device to wear it. The unobtrusive character of such an input device was emphasized by two participants.

every participant would wear a smart brooch

After trying out the four brooches (Figure 3.1) the majority of the participants said they like the flower most. They explained this with the haptic properties and possible functions of the brooch: The petals provide an easy way to grasp and turn the blossom and the users imagined a continuous value turning knob additionally to simple touch actions as input opportunities. Three participants preferred the spring because of the "satisfying haptic feedback". In addition to the implemented functionalities of touching and pulling the spring, one participant had the idea of knocking on the case of it. Overall, haptic feedback was mentioned in most interviews. Two participants explained this as an advantage over their smart watches because a brooch with tactile feedback could be used eyes-free.

Asking about where to wear such an Interactive Brooch, all participants chose the upper body like the chest or collar. Because of the similarities to smart watches, four participants also mentioned sleeves as possible position.

When being asked about the functions the participants would use the brooch for, everyone chose functionalities of their smartphone. People want to control their music, accept or reject calls, turn the volume up or down, mute their smartphone or activate voice input. Some participants additionally mentioned very specific functions like having a button, which reads the clock via headphones, controlling

brooches to control smartphone functions lights when riding a bicycle or using the brooch as remote release for a camera.

Participants imagined using the brooches in different situations. Some mentioned packed public transport where you do not want to pull out your smartphone, while others argued with social acceptability of pulling out the smartphone on a party or dinner. Generally speaking, participants imagined unobtrusive interactions in situations where they cannot or must not reach their smartphone.

At the end, participants were asked about problems of which they can think when wearing or using a smart brooch. Most participants mentioned false activations as possible threat. Participants also mentioned the convenience of the attaching mechanism or the robustness when accidentally washing the brooch. Two participants also were critical about the price to build or buy such a smart embellishment and one participant mentioned data privacy as critical factor.

Chapter 6

Summary and Future Work

6.1 Summary and Contributions

This thesis bridged the gap between interactions with conventional smart textiles and interactions with 3D-printed embellishments on smart textiles. Therefore, we used conductive polyester to expand capabilities of smart textiles by adding 3D-printed Interactive Brooches that provide eyes-free interaction with haptic feedback.

In order to understand the requirements for a good user experience of such brooches, we interviewed people and listed a wide range of aspects. We designed several example brooches, each of which provides unique feedback to improve the interaction. We explained how the prototypes were built and provided schematics for their electrical circuit layouts.

Recent work in smart textiles explored the use of conductive polyester to improve the mechanical and electrical contacting on smart textiles (Grimmelsmann et al. [2016]). We used the same technique to print brooches directly on fabric and explained how this solves the problem of attaching brooches on smart textiles. Additionally, other attachment techniques like pinning or sewing were explored.

We also presented a 3D-printed interface to improve the connection between soft textiles and stiff electronic components. Hence, we introduced a 3D-printed socket with a clipping mechanism for small PCBs. During the prototyping process we learned that the resistance of the printed polyester can be problematic. We reduced the total resistance by adding silver paint to the contact points and therefore decreasing the contact resistance. Additionally, we explained the best way to print with conductive filament.

The cost of the conductive filament is still higher, than regular PLA filament. Hence, only small parts of the brooches are printed with it. In our case, the brooches did use less than one gram of the conductive filament. Therefore the price for the presented brooches is still very low.

From the exploratory user study we learned that people are interested in smart embellishments as every participant said he would wear them. While the applications which participants imagined varied, everyone wanted to trigger functions of his smartphone.

One motivation for this thesis was to improve haptic feedback on smart textiles. This has been explicitly affirmed by the participants who welcomed "satisfying" feedback when using the brooches.

We conclude that Interactive Brooches promise new ways of physical interfaces on smart textiles with many advantages over regular smart fabric and even some advantages over State-of-the-art devices like smart watches. While these new interfaces are already accepted by participants of the exploratory study, future work should concentrate on haptic feedback and the ease of detaching the brooches.

6.2 Future Work

In Chapter 3.2 "Interaction Design" we explained that a continuous value input in circular motion is hard to detect with the technology used. The described method is based on the construction of mechanical potentiometers. These consist of a high resistance element and a sliding contact that moves along the element. In our approach, the difference in resistivity was hard to map to the rotation. We suggest that future work should take into account using different types of conductive filament. In this case, one could have a low resistance wiper which slides on a high resistance base and due to this improve the measurement.

limitations of the sused filament

One could also consider using different nozzle sizes for printing smart embellishments. As described in Chapter 4.2 "Attachment Techniques" the nozzle diameter determines the width of the printed lines. Most of current FDM printers come with a standard nozzle diameter of 0.4 mm but have the ability to swap the nozzle in seconds. With smaller nozzles (e.g. 0.25 mm) one can print finer details and therefore smaller brooches with smaller integrated wiring schematics.

vary nozzle size

The use of other printing techniques like laser-based stereolithography or even subtractive manufacturing methods can further improve the range of embellishments that can be used on smart textiles.

We hope that the current work will inspire expanding the research in smart textiles to smart embellishments in forms of Interactive Brooches as physical interfaces. Further studies and research in interaction design are needed to go along with this new form of wearable input devices that this thesis presents.

Appendix A

Interview Protocol

As part of my bachelor thesis I am researching Interactive Brooches. So let me first explain what that generally means. Interactive brooches are physical interfaces you can attach to your clothes. By physical interfaces i mean input devices that accomplish actions like controlling the music played by your smartphone. So to give you a brief overview of what we are doing now, after you signed the consent form, I will ask you several questions that might be interesting to me regarding my thesis. You can always take your time to answer the questions and of course it's no problem if you can't answer a question.
To start, here are some pictures of zippers, studs and brooches and I would like to talk about interaction capabilities. If you look at the pictures, could you explain just how you would manipulate them. You don't have to think about what you want to control or want to accomplish but only what you can imagine doing with them.

Can you think of other things attached to your clothes that can be manipulated and used as some kind of input? Maybe something you already have on your own clothes?

Here are some examples I thought of regarding my thesis and partly printed with a 3D printer. All of them have different actions you can do with them. Of course these are only prototypes and as we are in a very early stage of exploration I don't want you to focus on the visual aesthetics of them but I would like you to explore them and just tell me what you can do with them.

Which one do you like best and why?

Could you imagine wearing these?

Where on your clothes would you attach these things?

After seeing these examples if you could describe the perfect thing you would attach to your cloth and wear in your daily live, what would it look like? What would you change to make these things more attractive for you to actually wear?

Now I would like to focus on the things you could control with these new input modalities. No matter if ou think of the things from the pictures or the prototypes we have here. Can you think of an action you would want to control with a brooch attached to your clothes?

So here I have an example use case for one of them: You can control the music playback of this laptop with this button. You can play and pause by just touching the end and by pressing it down you can also skip a song.

After seeing this work do you have other ideas for actions you might want to do with Interactive Brooches?

At which times or at which places in your daily live would you like to have a fast and easy input technique like this for whatever action? Maybe in situations where you can't reach your smartphone?

So we mainly talked about new things you can do or would want to do, but for the last question i would like you to think about problems that might occur when wearing these input devices or when using them?

Do you have anything else to add we didn't talk about? Things you liked, things you disliked?

Thanks a lot for participating.

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