Chair for Computer Science 10 (Media Computing and Human-Computer Interaction)

RWTH AACHEN UNIVERSITY

Fabric Faces Library: Designing connectors for foldable textile structures

Bachelor's Thesis
submitted to the
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Registration date: 20.07.2020
Submission date: 20.11.2020

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Abstract

The Fabric Faces project consists of simplifying an object to a certain extend and then unfolding it to make it flat. The flattened model will be a kind of a wireframe model which will then be printed on top of textile. This flattened model can then be assembled using connectors on the edges. With this method, we will be able to save filament. Furthermore, this method makes the finished object lighter and more space saving. Using textile for the shell allows different aesthetics as well as soft surfaces. This thesis will concentrate on the connection of the edges. We designed a library of connectors which can be used for different applications in the construction process of an object. The connectors should make the flattened model easy to assemble and disassemble. While testing the different connectors in a user study, we found that some were better suited than others. In addition, we contributed to creating a process which simplifies the task of printing onto textile.

Überblick

Das Fabric Faces Projekt besteht darin, ein Objekt bis zu einem gewissen Grad zu vereinfachen und es dann auf zu falten, um ein flaches Modell zu erhalten. Das flache Modell ist eine Art Drahtmodell, das dann auf Textilien gedruckt wird. Dieses flache Modell kann dann mithilfe von Konnektoren an den Kanten zusammengebaut werden. Mit dieser Methode kann Filament gespart werden. Darüber hinaus macht diese Methode das fertige Objekt leichter und platzsparender. Die Verwendung von Textil für die Schale ermöglicht unterschiedliche Ästhetik sowie weiche Oberflächen. Diese Arbeit beschäftigt sich mit der Verbindung der Kanten. Es wurde eine Bibliothek von Konnektoren entworfen, die für verschiedene Anwendungen im Konstruktionsprozess eines Objekts verwendet werden können. Die Anschlüsse sollten das Aufbauen und Abbauen des flachten Modells erleichtern. Beim Testen der verschiedenen Anschlüsse in einer Benutzerstudie wurde festgestellt, dass einige besser geeignet sind als andere. Darüber hinaus wurde zur Schaffung eines Prozesses beigetragen, der das Drucken auf Textilien vereinfacht.

Acknowledgements

First and foremost, I would like to thank Prof. Dr. Jan Borchers for letting write my Bachelor Thesis at his chair.

I also want to thank Prof. Dr. Ulrik Schroeder for being my second reviewer.

Next, I want to express my sincere gratitude to my supervisor Adrian Wagner, for his constant support and guidance during the whole process of this thesis.

I also want to thank René Schäfer for kindly helping me out when I was facing problems regarding Fusion 360 add-ins.

Moreover, I enjoyed the weekly Club i10 meetings. Thank you all.

To those that did not hesitate to participate in my user study, I want to thank you for helping me out.

Last but not least, I want to thank my girlfriend Anne, my family and friends for the support over the last few months!

Conventions

Throughout this thesis we use the following conventions.

Textual ratings are written in *italic*.

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

The whole thesis is written in British English.

Links for used software or materials can be found in the footnote: Example Software[1]

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

Chapter 1

Introduction

3D printing has been becoming more and more popular over the last decade, as it is easy to operate and allows very quick prototyping for personal use and in industry. An advantage to mass production is that an item can be easily customised to fit every special requirement needed.

One problem with 3D printing is that it is very slow and it needs a large amount of filament for the creation of an object. Some multi material printers exist, but these are very susceptible to fails during the filament change. Additionally to the original print time of an object, for multi material print, a lot of time is added for changing the filament and purging enough to replace the previous filament completely.

Filament changes waste a lot of filament

Fabric Faces aims to solve some of the mentioned problems and brings a set of advantages. The basic idea behind Fabric Faces is to create only the outer shell of an object, which will then later be assembled into its final shape, as seen in figure 1.1. In Fabric Faces, an object is simplified into a wireframe of the original model. A flattened version of the wireframe is then created and printed, thus the final flat model consists only of printed edges. Said edges include a mechanic that allows attachment of neighbouring edges. The flattened object can then be assembled similarly to a papercraft object. The openings in the faces are covered by textile in order to create a complete shell.

Fabric Faces = 3D printed shell which can be assembled later

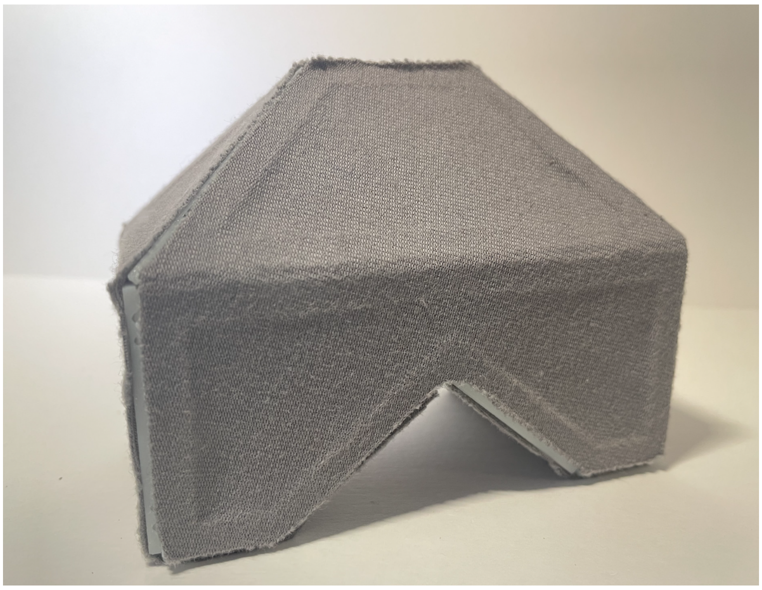

Figure 1.1: A picture of a finished Fabric Faces prototype, which was used for the user study

Cover faces of hollow object and save on infill & weight

As the Fabric Faces project uses textile to cover the faces of an object and the object is printed flat, the object will be completely hollow. This allowed the following advantage for our tested objects: the infill could be omitted completely, as the objects turned out very sturdy without internal support structures. Since the object and its faces are empty, the model also gets lighter depending on the used textile. A big advantage of textile in comparison to filament is that textile is cheaper than said polymer. Apart from the cost factor, fabric adds new possibilities in the creation of 3D models, as textiles give the object better aesthetics. It also allows a soft finish instead of printed hard faces.

Use conductive material for touch inputs

Various aesthetics with fabrics & flat model is space saving

With fabrics on the outside of the object, it also becomes possible to use conductive textile to create touch input on the object. This would be useful if microcontrollers were to be embedded. The fabric faces models could also be interesting for soft robotics, as one can easily create durable flexible joints with the help of textile. Another interesting point of Fabric Faces is that the finished model is completely flat before assembly. This allows compact shipping of the object, as it takes up less space than a complete 3D model. For instance, the object that we used for our user study would require a small box to ship, while the flattened object would fit in an standard C6 envelope.

In this work, we introduce a library of connectors which allow assembly and disassembly of flattened 3D printed objects. Moreover, we state different applications for the various connectors. Another goal of this thesis was to establish an easy process to print onto textile. Additionally, we tested the adhesion of the filament to different textiles. With the work done in this study, we seek the important parameters for the future software, which are important for the automation of the process of object creation, connector placement and separation of the flattened object into smaller islands to fit the print bed.

In the beginning of this thesis, we present some related work, to show what had already been done in the field of Fabric Faces and what sets our method apart. In the corresponding chapter, we go through the steps of 2D to 3D creation and embedding of different materials in 3D prints. We also demonstrate how fabrics had already been used in combination with 3D printing and lastly what methods already exist to assemble 3D printed models. After the related work, we quickly introduce the software, hardware and used materials, before presenting the tests and respective results of printing onto various textiles. Afterwards, we show the process of connector creation. Subsequently, we introduce our test model used for the user study, which was conducted to test the functionality of our designed connectors. We then present and discuss the results of said user study. Finally, the thesis concludes with a short summary of what has been done, as well as some future work.

Chapter 2

Related work

In Fabric Faces, we try to create a 3D model which results from a 2D state. This 2D state has embedded material to cover the faces of an object. In our case, said embedding material is textile. After the print is completed, the flat sample has to be assembled by connecting the edges. As these are some different research topics, the presented related work is separated into five sections: from 2D to 3D, embedding different materials in 3D prints, fabrics in combination with 3D printing, printing onto textile and connecting 3D printed objects.

2.1 From a 2D State to a 3D Model

Though the creation of the flat model, which will be turned into 3D object, will not be covered in this thesis, it is a main part of the project Fabric Faces itself. Therefore we want to present some approaches which cover this topic.

First, we present the LaserOrigami technique by Mueller et al. [2013]. It uses a laser cutter to create 3D objects by folding and cutting rigid sheets, instead of placing hinges. The heat of the laser cutter is regulated by defocussing the laser, in order to distribute the power across a larger surface. The cutting and bending can be done in

LaserOrigami shows us that we can get 3D model without using a 3D printer

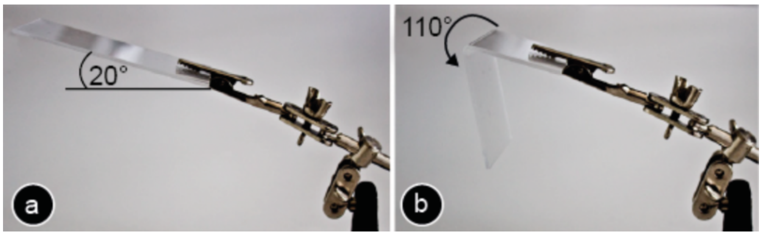

Figure 2.1: Bending after heating up fold area (picture taken from Mueller et al. [2013])

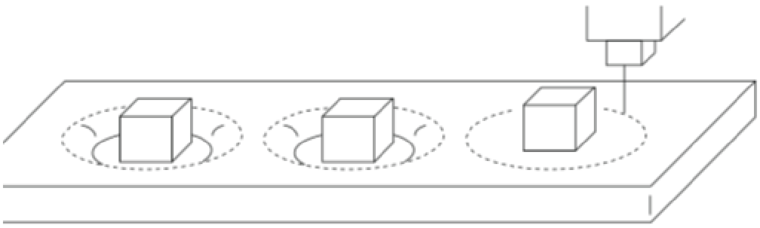

Figure 2.2: Stretching after heating up selected area (picture taken from Mueller et al. [2013])

Bending, stretching and suspending to create shapes

one single step, by moving the cutting table up and down. The LaserOrigami approach consists of 3 main elements, namely bend (figure 2.1), stretch (figure 2.2) and suspend (figure 2.3). For bending, they heat up an area until it bends due to gravity. Stretching can be done by heating up the outline until the patch stretches under its own weight. If the patch is not heavy enough, a weight can be added. Suspenders make suspension of surfaces possible by cutting a path and heating it up until the suspenders unfold. The distance of suspending is controlled by the length of the suspenders.

The following presented techniques will all involve a 3D printer, as this is how we create objects in our research. The two methods that are described in the next paragraph exploit the material properties of the used filaments in order to create 3D shapes.

First, we describe a method called Geodesy, which was developed by Gu et al. [2019]. It uses heat in combination with the anisotropic shrinkage of material to create bent areas.

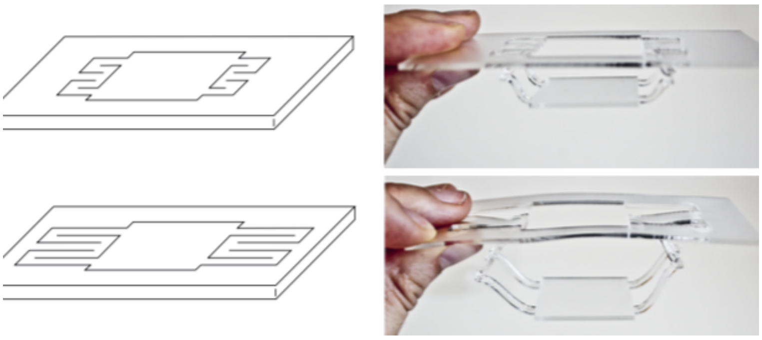

Figure 2.3: Suspenders lowering different distances (picture taken from Mueller et al. [2013])

To begin with, a flat tile is printed and afterwards exposed to heat. A tile consists of different layers with different thicknesses. The thinner the layer, the more it will shrink when heated. For convex shapes, the shrinkage rate has to decrease from the outer to the inner part of the tile. For concave shapes, this has to be inverted. A disadvantage of this method would be that it only gives a certain degree of control, so the end result can only be approximated. The second presented method to create 3D models from a flat state is called Thermorph by An et al. [2018]. This technique uses normal filaments like PLA and TPU. An object is printed out flat and then assembles itself automatically when it is exposed to heat, for instance when dipped into warm water. The goal of this method is to be able to use normal FDM printers, off the shelf printing materials and an automated printing process, with no pre or post processing. The self folding is realised with a bi-layer structure. TPU is used as an constraint layer, while PLA is used as an active layer. When PLA is printed, the polymer chains are pulled and straightened after being cooled down quickly. When it is reheated, residual stress is released, which results in shortening along the printing direction. This is due to the polymer chains returning to their chaotic state. The described behaviour is exploited to control the folding. Figure 2.4 shows how the flat model is turned into a 3D object when dipped into the heated water.

You can use different properties from polymers to achieve curvature from a flat model

PLA in combination with TPU can be used to control bending

A lot of other methods focus on using smart memory polymers to achieve a 3D state from a flattened model. Mao

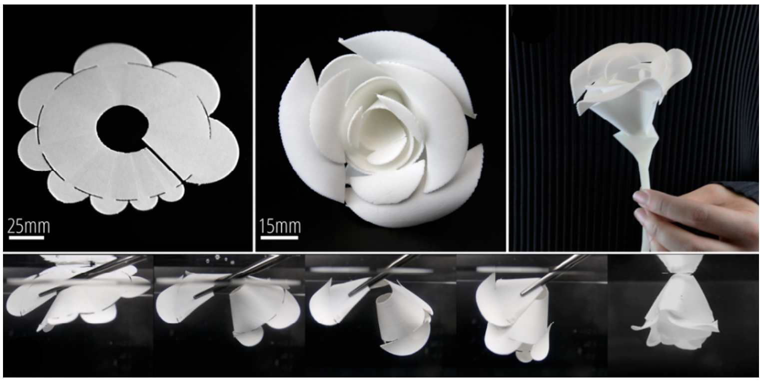

Figure 2.4: Sequence of the process to get a 3D rose from a flat model using the Thermorph technique (modified picture from An et al. [2018])

Smart memory polymers can be used to define the angles and bending locations between two faces, when the object is create in 2D

et al. [2015] used the behaviour of different polymers to control the sequence of the folding process. Liu et al. [2017] printed different colours onto folding locations on polymer sheets. As specific colours absorb only specific wavelengths of light, this was exploited to control the folding with respect to time and space. Yuan et al. [2017] were able to achieve multiple reversible shape changes and sequential folding by using active composites, like hydrogels or shape memory polymers.

Use outer shell with 3D printed inner parts

The last method presented in this section uses a shell to create a 3D object, which is what we do in Fabric Faces as well. Guseinov et al. [2017] showed a new approach to form curvy shells from an initially flat state, called CurveUps. Just like Fabric Faces, CurveUps uses some kind of outer layer to speed up the printing process. Guseinov et al. [2017]'s method consists of gluing 3D printed tiles onto a pre-stretched elastic sheet. The shape of the tiles and the restoring forces of the sheet then convert the sheet into a 3D model. When the model is in shape, the faces of the neighbouring tiles are in contact and define the angle between the tiles. The final state of the model then matches the target shape closely.

2.2 Embedding Different Materials in 3D Prints

As Fabric Faces will contain embedded material, this section will focus on the description of how different kinds of non-printed elements were coupled with 3D printed items.

Use soft material between faces on the edges to allow easy bending and folding

Deng and Chen [2013] described an approach to fold 3D printed sheets into origami models. A problem that they wanted to solve is that most 3D printed parts are rigid and do not allow being folded over and over again. They concluded that the folded areas require soft material, which allows bending in arbitrary angles. They used silicon rubber in their study, as this material is highly pliant and common. In a first step, a crease pattern is created, which defines how the sheet has to be folded. This pattern is then transferred into a CAD model. Then, structures are added to the edges where the sheet will be folded, so that the silicon will not separate from the rigid piece when being bent. These structures can be teeth or inlets, that allow a better connection between the two kinds of materials. Next, we looked into the study of Balderrama-Armendariz et al. [2019]. They investigated the folding endurance of different thermoplastics. In other words, they tested how often a hinge can be folded until it breaks. Objects created with the Fabric Faces method will be folded in order to create the 3D model. Instead of filament, we will use flexible soft fabrics to create the hinges in our project. This way, we avoid the problem of the hinges possibly breaking.

Thermoplastics cannot be folded infinitely many times

The next method describes the benefits of using different materials in combination with 3D printed objects. For instance, Fabric Faces can profit from the surface and flexibility of textile to create models.

Embedded materials bring practical properties to 3D printed objects, like sponges for soft areas

Chen et al. [2018] presented a whole library of materials that can be embedded into 3D prints. The current fabrication machines only work with a limited amount of materials. Their goal was to enable the use of everyday objects in 3D prints, as they could improve the characteristics for said printed items. Chen et al. [2018] demonstrated that the density of an object can be increased easily by simply

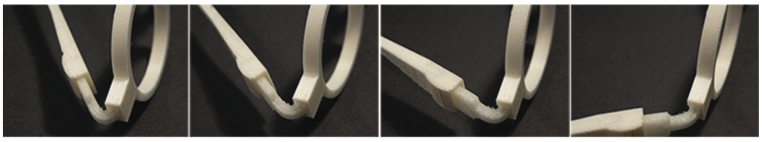

Figure 2.5: Wire embedded in print enables deformation (picture taken from Chen et al. [2018])

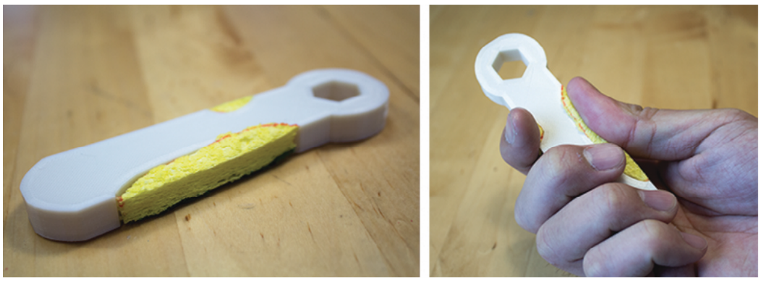

Figure 2.6: Sponge used in combination with 3D printed wrench to soften the grip(picture taken from Chen et al. [2018])

Adding wire could be another approach for the hinges of Fabric Faces

adding nuts as a weight during the print. Another interesting property they achieved is deformation, which was accomplished by integrating wires into elastic printed material (see figure 2.5). The wires allowed the print to stay in shape after being bent. The surface of printed objects can be softened by adding cut kitchen sponges to selected areas of the print. The embedded sponge can be seen in figure 2.6. Friction can be achieved by adding rubber and roughness by adding sand paper to the surface.

2.3 Using Fabrics in Combination with 3D Printing

3D manufacturing combined with textile is not new in research. It has already been used in different ways, of which we will present some approaches. The first two methods use textile as the print material. In contrast, Fabric Faces will use textile to cover the faces of a 3D printed object.

Figure 2.7: A printed teddy bear with the technique of Hudson [2014] (picture taken from Hudson [2014])

Hudson [2014] have built a new type of 3D printer. This 3D printer does not use the usual plastic filaments or metals, but it uses soft fibres to create 3D objects. The models are produced with a needle and felted yarn. It profits of the advantages of an FDM (Fused Deposition Modelling) printer, as the objects are created layer by layer. The resulting objects are flexible and soft and they look hand knitted. An example of a printed teddy bear can be seen in figure 2.7. One disadvantage of the approach of Hudson [2014] is that the produced objects are not precise enough for some scenarios.

Instead of filament use yarn as printing material

The approach of Peng et al. [2015] also uses fabrics to create 3D models. This method uses a sheet of fabric to form a layer of an object. The printer uses a laser cutter to cut along the outline of each layer. That layer is then attached to the previous layer with a heat sensitive adhesive. This step is repeated layer by layer, until the 3D object is completed. The Fabric around the object is not removed until the end of the fabrication process and is used as support material. The process can be seen in figure 2.8. After the completion of the manufacturing, the surplus of material has to be removed

Layered textile can create soft, but exact 3D models

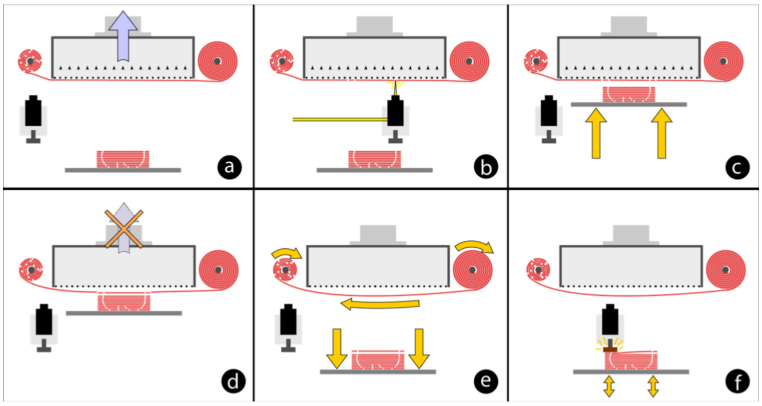

Figure 2.8: The process of how the designed 3D printer of Peng et al. [2015] works. Ascending letters show sequence of the steps (picture taken from Peng et al. [2015])

by hand. It is possible to include conductive fabrics in the manufacturing process in order to give the ability for touch inputs, which in return gives one the option to interact with the object.

New properties achieved by embedding textile into 3D printed models

Rivera et al. [2017] tried to combine 3D printed objects with embedded textile, as textile has many interesting properties like foldability, twistability, deformability, stretchability and cutability. The embedding of textile allows to profit of some of those properties for 3D printed objects. Rivera et al. [2017] presented some applications for the combination of 3D printing and textile and they investigated how to attach the fabric to the 3D printed models. While they touched on the subject that we want to examine in more detail in our research, they did not explore the technique in depth. They present some options of how to assemble their "shell print". This assembly is part of what we want to elaborate in this thesis. Rivera et al. [2017] also added printed plastics to textile in order to stiffen the fabric on the desired locations. Moreover, they showed how to create simple mechanical mechanisms by limiting the bending of fabrics. They further demonstrated that it is possible to create 3D objects that are bigger than the print bed of the used 3D printer by relocating the used fabric after one print step is done.

Simple mechanisms by limiting bending with 3D printed parts

2.4 Printing onto Textile

A lot of papers are dedicated to finding the optimal parameters in order to 3D print on top of textile to get the best adhesion between both materials.

Malengier et al. [2017] investigated three methods to test the adhesion of PLA and textile. The tests are the perpendicular tensile test, the shear test and the peel test. In the perpendicular tensile test, they test how much force, in perpendicular direction, is needed to pull the print off the textile. The shear test consists of pulling the fabric sideways away from the print. The peel test is similar to the shear test, with the difference that the textile is folded and pulled in the other direction, so it will loosen at the fold.

Perpendicular, peel and shear test to test adhesion of print to textile

Sabantina et al. [2015] tested which textile gives the best results concerning adhesion. Their study considered wool, cotton, viscose and polyester. The printing material used was PLA. Cotton and viscose did not result in a good adhesion as the printed patterns could be peeled off easily. Wool gave a better adhesion as this fabric has a rougher surface. The best results were achieved with polyester, as the PLA could flow into the material, which resulted in a proper mechanical connection. This was confirmed by Korger et al. [2016], who concluded that printing onto polyester gives the best adhesion results. They figured that the obtained adhesion strength is mostly determined by how well the printed material can wrap around the fibers of the textile.

Molten filament should penetrate textile easily to give good adhesion

Pei et al. [2015] tested different textiles, as well as printing materials, but did not experiment with the printing parameters. They found out that, out of their three tested filaments, PLA gives the overall best adhesion results. Textile-wise they concluded that poly-wool, a mixture of wool and polyester, and woven cotton works best.

PLA gives best adhesion to textile

The research of Grimmelsmann et al. [2018] mainly laid focus on finding the optimal z-distance to the print-bed. When the distance is too large, larger than the sum of the fabric thickness and the first layer thickness, the material

optimal z offset $\approx$ first layer height + textile thickness does not bond with the textile at all. Only wool allowed a connection above that height. When the distance is too small, the textile blocks the printing material from flowing out of the nozzle, which can result in a clog. They achieved the best adhesion with thick pure polyester.

The printing parameters for printing onto textile are just as important as the textile itself

Spahiu et al. [2017] investigated different printing parameters, that can be influenced easily. First of all, slower printing and different polymer flows only give a marginal difference in terms of adhesion. Contrarily, increasing the nozzle temperature results in a big adhesion difference. This is because the molten PLA has a reduced viscosity and can flow better into the textile. An increase of temperature of the print bed gives the biggest difference in adhesion, as a temperature of 100° nearly doubles the adhesion force compared to 60°. The filament remains in its molten state for a longer time and can therefore penetrate the fabric better. The standard extrusion width of 0.4 mm gives the best adhesion, but only marginally. Another important factor is the first layer height. Smaller than 0.2 mm nearly makes no difference in adhesion, but increasing the layer height reduces it drastically.

Though polyester was mentioned by most as one of the best choices, there does not seem to be a complete consensus on the optimal textile to be printed on. For the printing material though, PLA seems to be the best choice.

2.5 Assembling 3D Printed Objects

To conclude the related work chapter, we present a couple of approaches for the assembly of 3D printed objects. Though some research has been dedicated to this topic, none is completely compatible to the kind of connectors that we design. In the following paragraphs, we will therefore present two approaches which come closest to assembling a 3D model consisting of multiple parts.

First of all, Song et al. [2015] used an interlocking method to assemble an object which had to be separated, to fit the print bed for instance. They did not want to use glue or con-

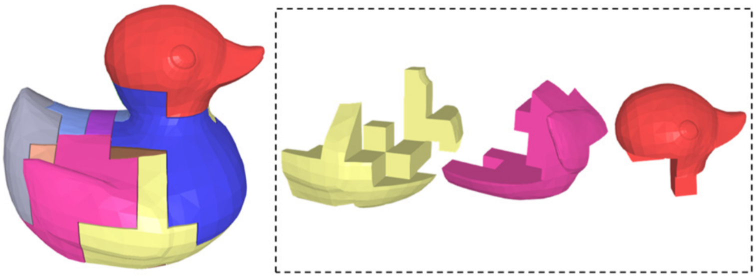

Figure 2.9: Assembled object on the left side, single pieces on the right side (picture taken from Song et al. [2015])

nectors, so that the 3D printed objects could be assembled and disassembled over and over again. They did want the connection to be strong. So, Song et al. [2015] developed an approach to partition a given model into interlocking parts. Said method can be seen applied in figure 2.9.

Multiple assemblies and disassemblies will also be of importance for Fabric Faces

Luo et al. [2012] developed another approach, called Chopper, to partition an object and assemble it after the printing is done (see figure 2.10). Chopper uses connectors on the separate parts of a object. The connectors can have different shapes. Depending on their shape, the connector gives enough strength to hold the objects together, or it can only be used as a guide for assembly, to attach the parts with glue.

Shape of connector determines strength of connection

Fabric Faces will use a different approach for the connections for the final assembly of an object, namely the use of various connectors on the edges.

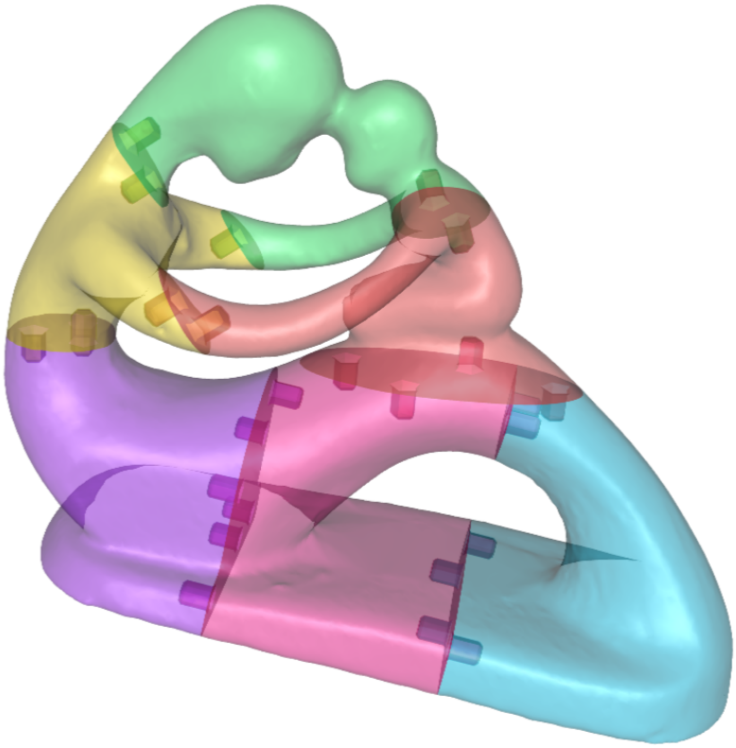

Figure 2.10: Figure separated with placed connectors using the method of Luo et al. [2012] (picture taken from Luo et al. [2012])

Chapter 3

Technical Background

In this chapter, we want to present the used printer and materials, as well as the used CAD software. Furthermore, we show how the settings for the slicer software had to be altered in order to print onto textile. Afterwards, we proceed with the textile tests, which were done to select which textile was best suited for our purpose.

3.1 Materials and Software

All designed pieces were created with Autodesk Fusion 360[1] as everything can be easily parametrized and changed during the design process. We used different kinds of textiles for our study. They are listed in Table 3.1. The thickness of the textile was measured with a Digital Caliper. The printer we used was the Original Prusa MINI[2], in combination with the PrusaSlicer 2.2.0[3] software. As many studies suggested, we used PLA as printing material. The used filament was TierTime[4] (PP3DP) UP PLA White.

[1] https://www.autodesk.de/products/fusion-360/overview
[2] https://www.prusa3d.com/original-prusa-mini/
[3] https://www.prusa3d.com/prusaslicer/
[4] https://www.tiertime.com/

Name	Material	Weight	Measured Thickness
Polyester allround	100% Polyester	156 g/m^2	0.32 mm
Fleece antipilling	100% Polyester	261 g/m^2	2.60 mm
Cotton jersey	95% Cotton 5% Elastane	220 g/m^2	0.62 mm
Cotton fleece	100% Cotton	280 g/m^2	2.94 mm
Glen plaid	80% Polyester 20% Polyacrylic	238 g/m^2	0.71 mm
Jacquard plaid	80% Polyacrylic 20% Polyester	295 g/m^2	1.04 mm

Table 3.1: Tested textiles

Adapt start G-code to ease placement of textile

In order to be able to place the textile onto the printing bed, we first had to adapt the start G-code. Before then actually placing the textile, the printer has to have completed the following steps:

1. Auto Bed Leveling
2. Purge Line
3. Pause (M601)

Fix textile to print bed with magnets and double sided tape

While the printer is paused, one can easily remove the purge line and place the textile onto the printing bed, fixating it with 8 to 18 Neodym 10x2 mm magnets and double sided tape to reduce warping. Due to the textile thickness, some more z-offset than usual is needed as printing does not occur directly onto the printing bed. In PrusaSlicer, we added the thickness of the textile under:
Printer Settings → General → Size and coordinates → Z-offset.

We then applied the printer parameters according to Spahiu et al. [2017]:

- Standard velocity
- Elevate extruder temperature to 220 °C
- Set extrusion multiplier to 100% for the first layer, standard flow afterwards

- Elevate bed temperature to 100 °C (do not reduce afterwards as warping occurred while printing)
- Standard extrusion width
- First layer height should be equal to or less than 0.2 mm

For all tested prints, we used a layer height of 0.15 mm.

3.2 Textile Tests

This section will focus on the pre-tests we did with the textiles, described previously. This was the beginning of the study, as we first needed to find a suitable textile for further experiments.

To test the adhesion for different shapes, we used three different tests, namely the line test (figure 3.1 a), the square test (figure 3.1 b) and the random shape test (figure 3.1 c). The line test consists of a line which has a width of 5 mm and a length of 100 mm. The square test object is a hollow square with a side length of 50 mm and a line width of 5 mm. The random shape test object is formed like a very simple fish and has a line width of 2 mm. The random shape test was used to see how well rounded lines, sharp corners and small details could be printed on textile. All tested shapes had a height of 1 mm.

Three test objects: line, square and random shape

We used a simplified version of the tests from Malengier et al. [2017] to test the adhesion of the print to the textile. As perpendicular force is not important for our use case, we did not conduct this test. For us, the shear and peel test are important, as vertical pulling should not happen while assembling an object. The measuring was done with a precision spring scale which allows measuring up to 5 N. The line and square test gave us no results as all measured values were above 5 N. This means that the provided parameters by Spahiu et al. [2017] give us a good adhesion for our needs. For the random shape, the shear test also only had results over 5 N. Table 3.2 shows the results from the

Perform shear and peel test with objects

Parameters from Spahiu et al. [2017] give good results

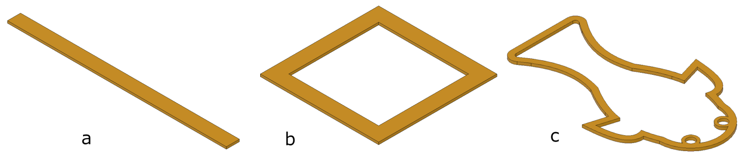

Figure 3.1: The different test objects: Line test (a), Square test (b), Random shape test (c)

peel test for the random shape printed onto different textiles. The best result was achieved by the *Fleece Antipilling* as this textile also exceeds the 5 N for this test.

Textile	**Peel Test**
Polyester Allround	0.9 N
Fleece Antipilling	>5 N
Cotton Jersey	0.7 N
Cotton Fleece	1.5 N
Glen Plaid	1.8 N
Jacquard Plaid	2.6 N

Table 3.2: Values found for the peel test for the different textiles on the random shape test

Polyester Allround & Jacquard Plaid fray when being cut

The *Polyester Allround* and *Jacquard Plaid* textiles have one major problem. After cutting said textiles, the border immediately started to fray. As for Fabric Faces the textile will be cut around the print, the fraying could lead to the fabric releasing from the printed material.

All attempts to remove warping failed

A major problem we were facing was that bigger objects started warping while being printed onto textile. As we first did the tests with the thin shapes shown in figure 3.1, the warping was only noticed when we turned to higher and larger objects. For the initial tests with the thin shapes, we used small magnets to successfully fixate the textile to the print bed. The next object that was printed was a flat model of a small cube, during whose printing major warping occurred. This led to it being impossible to properly assemble the cube, as the edges did not fit anymore. After noticing this problem, we tried to solve it by heating the print bed to initial 100°for the first layer, reducing it to 60°for the remaining print. With this method, we did not see a difference, meaning that warping was still a problem. The next attempt was to print onto a non-heated print, which made the warping even worse. Additionally, the filament's adhesion to the textile was strongly reduced.

We then approached the problem by using double-sided tape to fixate the textile onto the print bed. First, we tried putting the tape onto the cold print bed, which led to air bubbles under the tape. Consequently, we removed and reapplied the tape to the heated bed instantly, which solved the bubble difficulty. The next problem arose due to the strong adhesion of the tape to the textile. We were not able to remove the textile without damaging the connection between fabric and print. Additionally, warping still occured, even when using the tape. The textile which showed the least warping was the *Cotton Jersey*. This is why we then chose this textile for our further experiments. We then decided to glue the textile to the printed parts for the user study (chapter 6). This had to be done in order to ensure that the deformation did not interfere with the results of the connection.

We continued with *Cotton Jersey* as this textile had the least warping

What we further could have tested in order to reduce or even completely remove warping, would have been to print in a heated print room. As we did not have access to the latter, this could not be done.

Chapter 4

Connectors

Following the textile tests, we want to present the different connectors that we developed during this study. This chapter will also include the important parameters for said connectors.

4.1 Two classes of connectors

There are two main base structures of connectors, nubs and slats. Nubs are cylindrical objects which interlock or fit into a female version of the connector. Slats are cuboids that fit into a female connector piece. For simplicity, the face where the connectors are placed all have a width of 5 mm. Behind the connector face, some extra space is needed for the connectors which consist of a male/female version. This extra space (ES) can be calculated by

Extra space, in order to have enough space for the female connector

$$\mathrm{ES} = \mathrm{CH} \cdot \sin(\frac{1}{2} \cdot \mathrm{Angle}) + \mathrm{EW} \tag{4.1}$$

In the formula, Angle is the angle which the connector should form and connector height (CH) is the height of the connector itself, without the piece beneath which forms the angle. Extrusion width (EW) is needed so that the wall behind a female connector has at least one printed line.

Another formula that is used for every connector is taper

Taper angle to set amount of overlap for connectors

angle (TA). The taper angle for a certain overlap percentage (OP) can then be calculated by the following formula.

$$\mathrm{TA} = 90^\circ - \tan^{-1}(\frac{\mathrm{CH}}{\mathrm{OID} \cdot \mathrm{OP}}) \tag{4.2}$$

This angle determines how much the interlocking connectors will overlap. The outer-inner distance (OID) is the distance between two connectors of the same side.

4.1.1 Nubs

As already mentioned, we designed two kinds of nub connectors which are completely different to each other.

Calculate the taper angle and distances in order to generate interlocking nubs

The first version of this connector uses interlocking cylinders. Those cylinders have a diameter of 1.9 mm, which is 38% of the width of the connector, and have a height of 1.5 mm. The 38% were determined by testing empirically. The nubs for this connector are positioned in a way that there are four outer cylinders and one cylinder in the center. The outer nubs are arranged in a square while the central one is positioned exactly in the middle of the four outer ones. The distance between two outer cylinders is 1.2 mm. The base of the cylinders is adjacent to the side of the connector (5 mm - 2 · 1.9 mm = 1.2 mm). The distance from an outer cylinder base to an inner cylinder base can be calculated by

$$\mathrm{OID} = \frac{\mathrm{Width} - \mathrm{Diameter}}{\sqrt{2}} - \mathrm{Diameter} \tag{4.3}$$

In our case, this results in 0.292 mm. As cylinders would not interlock when they are straight, a taper angle is required. The best overlap percentage for this size of nubs was determined to be around 70%, which results in a taper angle of 7.8°. If it is a lot less, the nubs will not interlock, if the angle becomes too large, the connectors cannot be assembled anymore.

1 & 2 row male/female version with nubs to eliminate space created by interlocking version

The second version of the connector using nubs consists of a male and a female part, in order to remove the spacing added by the interlocking version. This connector was tested with one row of nubs (see figure 4.2) and two rows of

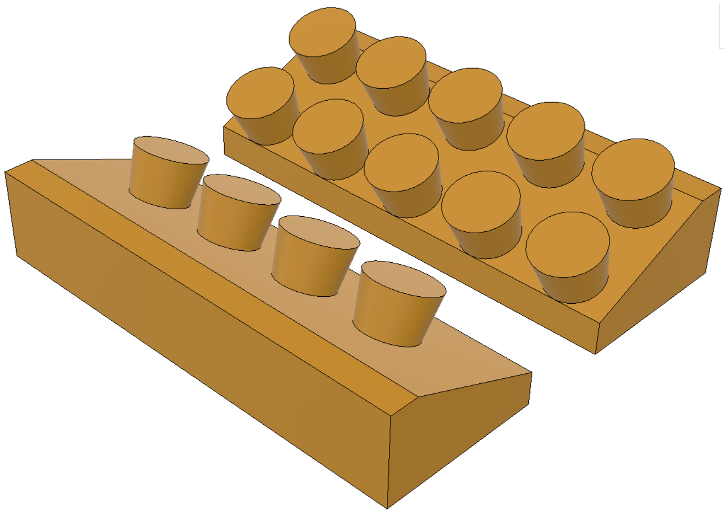

Figure 4.1: Interlocking nub connector, which forms 45° when assembled

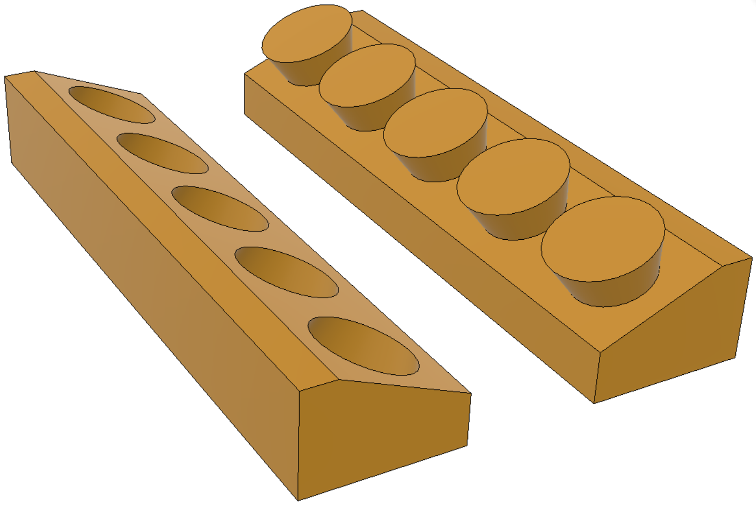

Figure 4.2: Male/Female nub connector with one row of nubs, which forms 45° when assembled

nubs (see figure 4.3). The male side of the two row version coincides with the outer nubs of the interlocking first version. This means that the calculations for this side remain the same. For the female side, the connector has inlets into which the male side enters. To make this possible, the hole

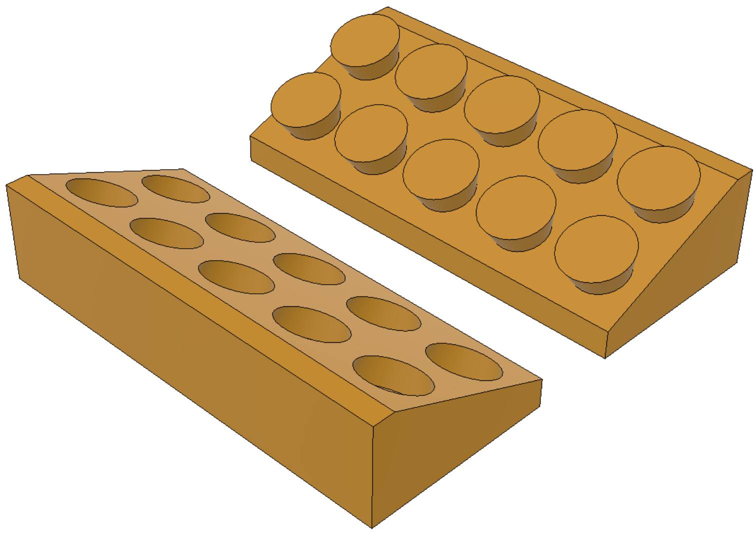

Figure 4.3: Male/Female nub connector with two rows of nubs, which forms 45° when assembled

FD used in order to have a small tolerance to permit fitting the male side inside

for the female side has to be slightly bigger than the male counterpart, as the male cylinder is bigger at the top than at the bottom. The female diameter (FD) can be calculated by the following formula:

$$FD = \text{Diameter} + 2 \cdot NH \cdot FDP \cdot \tan^{-1}(TA) \quad (4.4)$$

The formula expresses the diameter of the nub at female diameter percent of the height of said nub. This entails that if female diameter percentage (FDP) would be 75%, then the female diameter at the opening of the hole would have the diameter at 75% height of the male nub.

4.1.2 Slats

Three different designed slat connectors use male/female concept

The second class of connectors uses slats, meaning cuboids which are placed on the connectors face. For this method, we used three different approaches, vertical slats (see figure 4.4), vertical slats with a slope (see figure 4.5) and horizontal slats (see figure 4.6). All connectors use the male/female approach. A first model was designed with interlocking cuboids, but as these added too much space in between the connector faces, this connector type was not developed any further.

Same calculations for the three kinds of slats

The calculations for all 3 kinds of connectors are the same. The male connectors have a width of 2 mm and a height of 1 mm. The length of the male connectors is 3 mm. The taper angle is 26.6°, which comes from an overlap percentage of 25%. The outer-inner distance (OID) for the slats is simply the width of the connector. These values were determined for the interlocking slat connector and were transferred to the male/female version, just like for the nubs.

Calculation for female side the same as for female nub side

In the following, the female side of the connectors will be described. The female width can be calculated in the exact same way as the diameter for the female nubs, by exchanging the diameter in the formula by the width of the slat. The female width percentage was chosen to be around 60% as this gave the best connection and a satisfying clicking noise when putting the connector together.

The sloped slat connector only works for small angles

The slat with slope has a slope that expands over the whole length of the connector. The height was the smallest on the inside of the connector and the highest on the outside. This connector performed the worst in our conducted pretests (see table 4.1) and was not considered for further investigation. It could be a useful connector for an edge of an object which should be easily openable. This connector only works well for small angles which can be seen in section 4.2.

4.2 Technical Evaluation

In this section, we present our results of the pretests we did with the various connectors. The results are summarised in table 4.1 (Slats) and in table 4.2 (Nubs). All connectors were printed with the parameters which were presented in the preceding sections of this chapter.

The top row specifies what connector refers to which column. The connectors were tested in 20° increments starting at 30° up to 150°. For each tested angle, we investigated

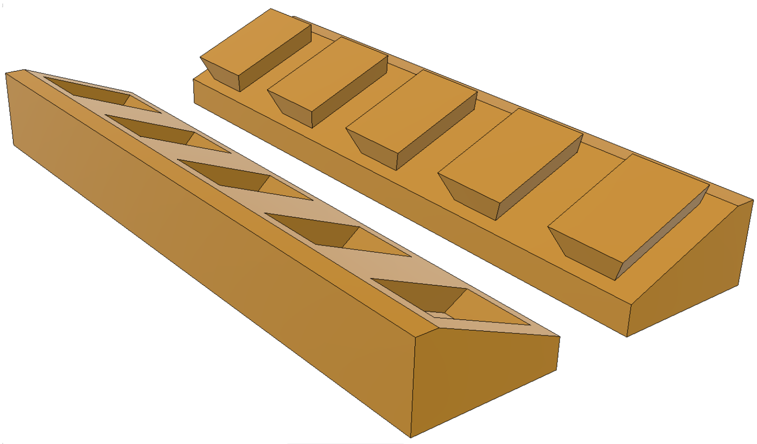

Figure 4.4: Slat connector with vertical slats, which forms 45° when assembled

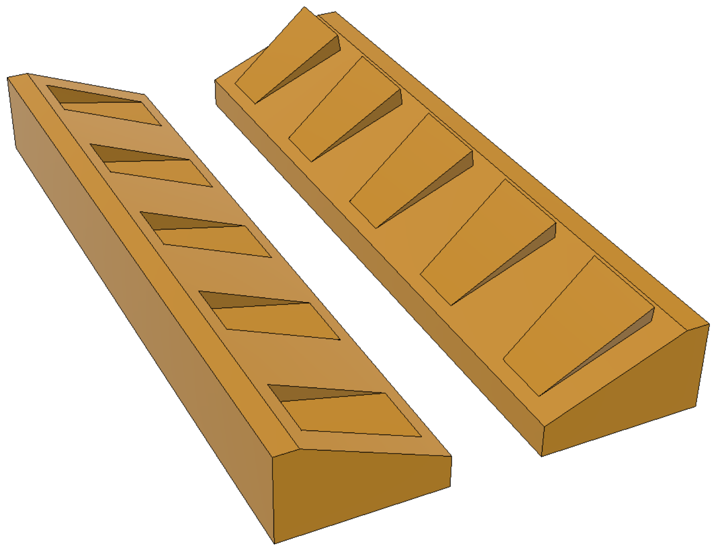

Figure 4.5: Slat connector with vertical slats and slope, which forms 45° when assembled

the precision of the angle, an estimation of the strength of the connection and of how easy the connectors can be assembled and disassembled. The precision of the angle was measured with an angle protractor ruler. The connection strength was ranked from *Weak* to *Very Strong* and the assembly and disassembly were ranked from *Too Easy* to *Very*

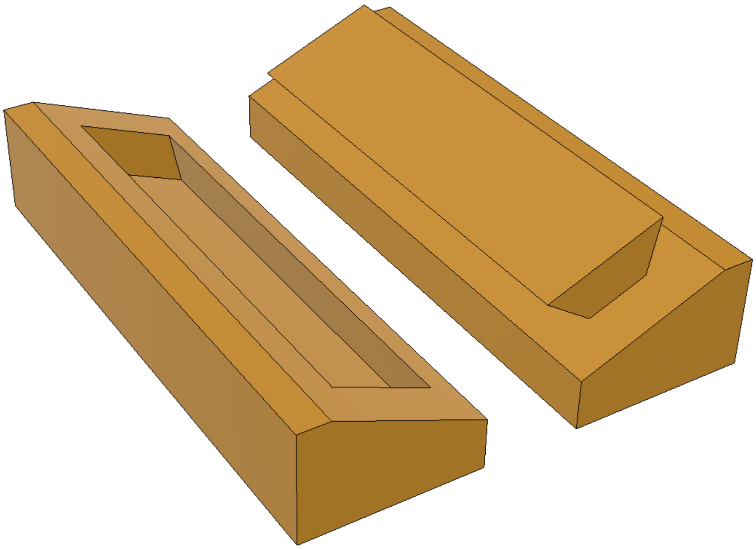

Figure 4.6: Slat connector with horizontal slat, which forms 45° when assembled

Hard. A "/" in a cell means that the assembly was not possible anymore, respectively there was no connection.

Up until 130° all connectors, besides the sloped slat connector, gave a good connection. The connection of said sloped slat was already weak at 70°. The angles formed by the connectors were very precise. In our opinion, based on the pretests, the overall best and most consistent results for the different angles were achieved by the vertical slat connector without slope.

Good connection from all connectors beside sloped one up to 130°

4.3 Obtuse and Concave Angles

Obtuse and concave angles are special cases for the connectors, as 3D printers have problems printing arbitrary angles starting as soon as the angle gets too big. While doing some pretests, the connection started to drastically weaken starting at about 130°. To solve this problem, we added bridges to enable bigger angles. There are two kinds of bridge pieces.

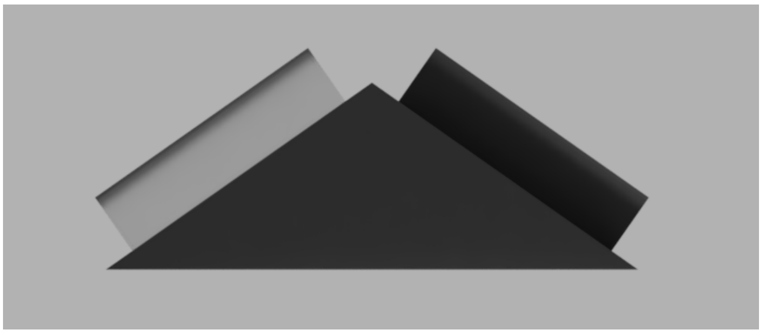

Figure 4.7: Side view of bridge piece for big angles, in this case with slats as connector

Figure 4.8: Side view of bridge piece for concave angles

Big angle bridges for angles over 120°

The bridge piece for big angles (< 250°), is shaped like a triangle from the side view (see figure 4.7). The faces of this bridge piece form 110° on the inside, as 110° connectors can be printed easily and still give a very good connection. Connectors can be printed with a good connection up to 120°. This entails that for an angle of 121°, one uses a connector of 11° in combination with a big angle bridge. This piece is simply clipped in between the faces of the connectors to enlarge that angle.

Concave bridges for angles over 250°

The bridge piece for concave angles is more or less the counterpart to the obtuse angle bridge. The faces also form 110°, but in this case on the outside of the piece (see figure 4.8). This piece is used for angles greater than 250° and up to 360°, which probably is unnecessary.

In order to make it clear to the end-user where to put which bridge piece, we came up with the following solution. The edges of the object which require a bridge have the same side of the connector on both sides. For big angle bridges both sides have a female connector, meaning the bridge piece has two male connector pieces. This is inverted for concave bridge pieces. Here the bridge piece has two female sides and the object two male sides. With this technique, the object cannot be assembled without the needed bridge pieces and the placement of the two kinds of bridges is also unambiguous.

Big angle bridges with 2 male sides and concave bridges with 2 female sides for unambiguously placement

Angle	Test	Horizontal Slat	Vertical Slat - No Slope	Vertical Slat - Slope
30°	Real Angle:	31°	30°- 31°	31°
	Connection:	Good	Very Good	Good
	Assembly:	Easy	Easy	Easy
	Disassembly:	Easy	Medium	Easy
50°	Real Angle:	50°	49°- 50°	50°- 51°
	Connection:	Good	Very Good	Good
	Assembly:	Easy	Easy	Easy
	Disassembly:	Medium	Medium	Easy
70°	Real Angle:	70°	70°- 71°	70°- 71°
	Connection:	Good	Very Good	Weak
	Assembly:	Easy	Easy	Easy
	Disassembly:	Medium	Medium	Too Easy
90°	Real Angle:	89°- 90°	90°	91°
	Connection:	Good	Very Good	Weak
	Assembly:	Easy	Easy	Easy
	Disassembly:	Medium	Medium	Too Easy
110°	Real Angle:	111°	110°- 111°	112°
	Connection:	Good	Very Good	Weak
	Assembly:	Easy	Easy	Easy
	Disassembly:	Easy-Medium	Medium-Hard	Too Easy
130°	Real Angle:	131°	130°- 131°	/
	Connection:	Good	Very Good-Strong	/
	Assembly:	Easy	Easy	/
	Disassembly:	Easy-Medium	Medium-Hard	/
150°	Real Angle:	151°- 152°	150°- 151°	
	Connection:	Weak	Weak	/
	Assembly:	Easy	Easy	/
	Disassembly:	Easy	Easy	/

Table 4.1: Pretests of the designed slat connectors

Angle	**Test**	**Nubs - Interlocking**	**Nubs - Male/Female**	**Nubs - 1 Row**
30°	Real Angle:	29°- 30°	30°	130°- 131°
	Connection:	Very Good	Very Strong	Strong
	Assembly:	Easy	Medium-Hard	Medium
	Disassembly:	Easy	Very Hard	Medium
50°	Real Angle:	50°- 51°	50°- 51°	50°- 51°
	Connection:	Very Good	Very Strong	Strong
	Assembly:	Easy	Medium-Hard	Medium
	Disassembly:	Easy	Very Hard	Very Hard
70°	Real Angle:	69°- 70°	70°- 71°	70°- 71°
	Connection:	Very Good	Very Strong	Strong
	Assembly:	Easy	Medium-Hard	Medium
	Disassembly:	Easy-Medium	Very Hard	Medium
90°	Real Angle:	90°- 91°	90°	91°
	Connection:	Very Good	Very Strong	Strong
	Assembly:	Easy	Medium-Hard	Medium
	Disassembly:	Easy-Medium	Very Hard	Medium
110°	Real Angle:	110°- 111°	109°- 110°	110°- 111°
	Connection:	Medium	Strong	Good-Very Good
	Assembly:	Easy	Medium	Easy-Medium
	Disassembly:	Easy	Medium	Medium
130°	Real Angle:	129°	128°- 129°	133°- 134°
	Connection:	Weak	Good	Good
	Assembly:	Easy	Medium	Easy-Medium
	Disassembly:	Easy	Medium	Easy-Medium
150°	Real Angle:	151°- 152°	/	/
	Connection:	Weak	/	/
	Assembly:	Easy	/	/
	Disassembly:	Easy	/	/

Table 4.2: Pretests of the designed nub connectors

Chapter 5

Test Object

After having established all the basics to construct a flattened model, we had to come up with an easy object to simultaneously test acute, obtuse and concave angles.

5.1 Presenting the Test Object

Simple object to test acute,obtuse and concave angles

We chose the object to be a very simplified form of the *Ponttor*, located in Aachen, Germany. The object can be seen in figure 5.1. Even though the object has a lot of right angles, it also considers acute, obtuse and concave angles, which means that the special cases are covered.

Location	**Angle**
archway top (a)	260°
archway bottom (b)	140°
wall to roof (c)	140°
roof big to big side (d)	80°
roof big to small side (e)	114.404°

Table 5.1: The different angles of the test object. The exact locations marked by the letters can be found in figure 5.1.

The different angles, which are not 90°, for the tested object

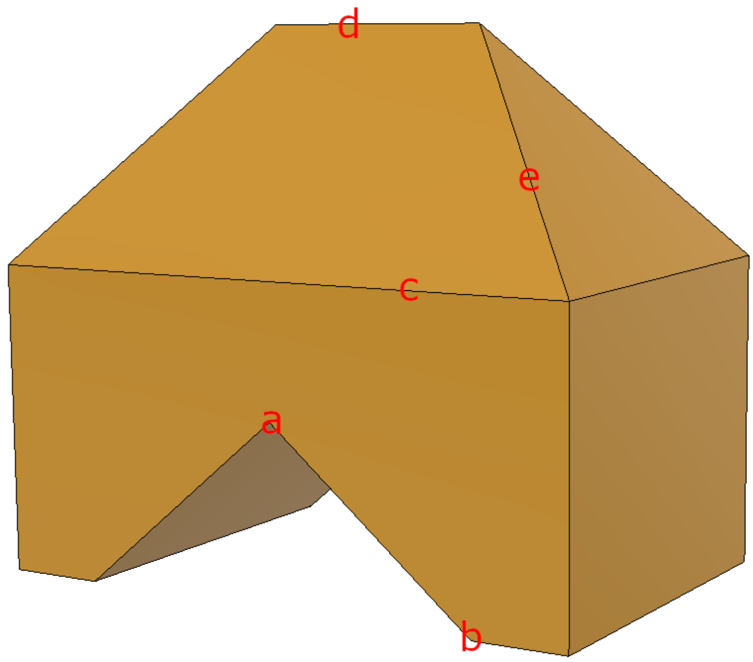

Figure 5.1: The simplified version of the *Ponttor* used for the user study. The letters mark the spots of the angles from table 5.1

can be found in table 5.1. The angles are always measured on the inside of the object.

5.2 Design Process of the Test Object

Separation distance between faces depends on the angle the faces should form

In a first step, the object was designed as whole piece using Fusion 360[1]. Afterwards, it was transformed into a papercraft object with one of the pre-installed Blender[2] plugins. The created model could then be used as a template to construct the unfolded *Ponttor* object. The papercraft template can be seen in figure 5.2. To make the assembly possible, the different edges of the model have to be separated. The separation distance depends on the angle of the faces that have a common edge. This separation-distance (SD) can be

[1]https://www.autodesk.de/products/fusion-360/overview
[2]https://www.blender.org/

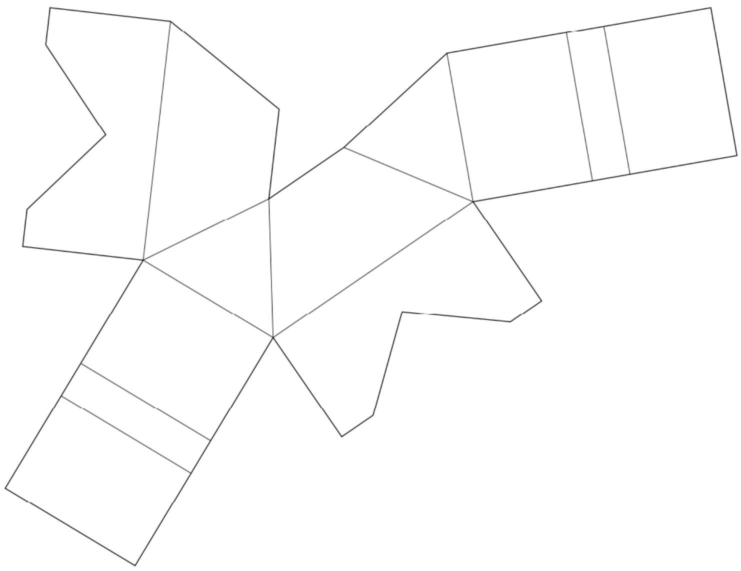

Figure 5.2: The papercraft model of the object in figure 5.1

calculated with the following formula.

$$SD = 2 \cdot \text{MinHeight} \cdot \cos(\frac{\alpha}{2}) \tag{5.1}$$

MinHeight describes the height of the part under the actual connector and α is the angle which should be formed by the two adjacent faces.

In a next step, the connector bases without connectors were added. These angled pieces will define the angle after the assembly of the object. One problem we faced in this step was that when two neighbouring edges formed different angles, the neighbouring connector bases had different heights. Thus, the intersection of both edges had to be adapted in a fashion that the higher connector (bigger angle) did not interfere with the lower connector (smaller angle). This can be seen in figure 5.3, marked by the green circle. Another special spot in this model is where the archway meets the front wall. As connectors are not as thin as paper and require some space, the tip could be as sharp as on the original model, but had to be flattened. The flattened arc can be observed in figure 5.3 marked by a red circle. In order to be able to fit the concave connector and bridge, that

Edges with different angles have different heights

Concave edges need some more space to make assembly possible

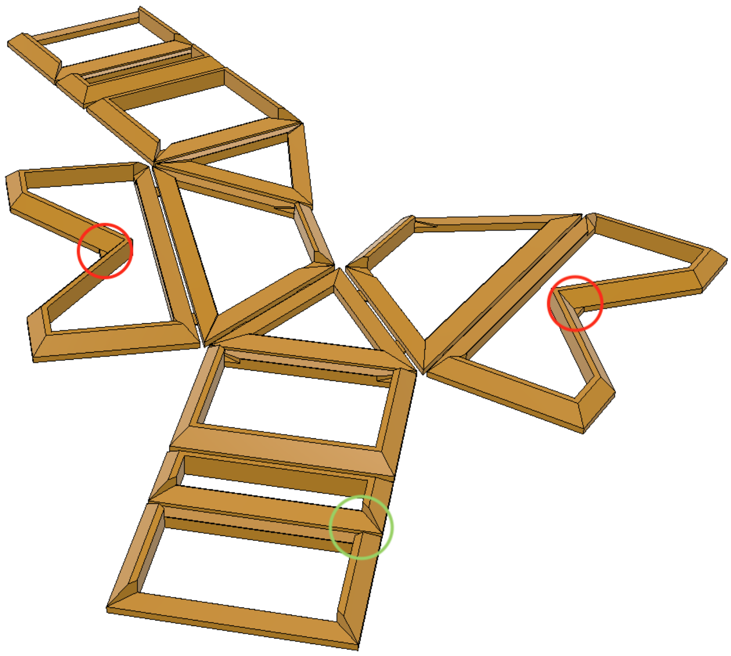

Figure 5.3: The finished flat model without connectors added. In the green circle you can see the height difference of the connectors and in the red circle you can see the adapted tip of the arc.

flattening line has a length of 3 · MinHeight. This ensures that the end user is able to place the connectors onto the bridge.

The finished model without connectors can be found in figure 5.3.

2 sets of connectors per edge usually give enough strength for connection

In the last step, the connectors had to be added to the corresponding spots on the model. This step had to be repeated for every designed connector. In a small pretest with a cube, we found out that for most cases two connector pairs per edge give enough strength to hold the object together tightly. It is worth mentioning that the complete flat model had a size of roughly 240 mm times 240 mm, which is too big for most standard printers. This required the separation of the object into two parts to fit the small print bed of the Prusa MINI.

Chapter 6

User Study

After having designed the test model, described in the preceding chapter, we could use it to conduct a user study. The goal of the study was to analyse the effectiveness of the various designed connectors. We wanted to investigate whether they show different results in providing sturdiness to the assembled 3D objects. Moreover, ease of assembly and disassembly were investigated depending on connector type.

6.1 Methodology of the User Study

To start the user study, we explained the information on the informed consent form (see appendix A), and provided the participants with a printed version. The form contained details about the procedure and the purpose of the study. After signing the consent form, the participants were then handed out a questionnaire (see appendix B), where they first had to disclose some demographic information. Additionally, they had to rate their experience with 3D modelling, 3D puzzles, as well as their general experience with crafting.

Said questionnaire was used to rate the connectors and take notes during the user study. As there are five different connectors, each person had to assemble and disassemble five models while being timed for each step. The questionnaire subsequently also contained five sets of questions about the assembly, the connector and the disassembly. In what order the models with the different connectors were handed out to each participant was determined by a Latin square. This assured that every possible sequence for the connectors was taken into consideration.

As such, the participant had to assemble and disassemble one object, answer the corresponding questions and repeat this process for all five models. Before beginning the first assembly, each participant was allowed to look at an already assembled model, in order to see what the finished object should look like. Afterwards, they were handed their first flat model with the first set of connectors. After having assembled and disassembled all five different models, the participants were asked to rate the connectors from 1 (best) to 5 (worst).

Chapter 7

Evaluation

In this chapter, we will present the results retrieved from the preparation and the completion of the user study described in the preceding chapter. In addition, we will talk about the encountered problems with the connectors, as well as present some possible applications for the different versions.

7.1 Printing the Object

In order to later print the test object, we sliced the complete model, as well as the flattened model for comparison. Both models were sliced with the standard 15% gyroid infill. To our surprise, the print time of the flat test model was nearly the same as for the complete model. Nevertheless, the flat model only needed around 10m of filament to print, while the complete model used around 18m of filament. So, even though we could not save any time, we achieved significant filament saving of approximately 45% for this model. The finished print for the 2 row nub connector can be seen in figure 7.1.

No time saving for our test model because variable layer height used up all saved time

Saved approximately 45% filament for this model

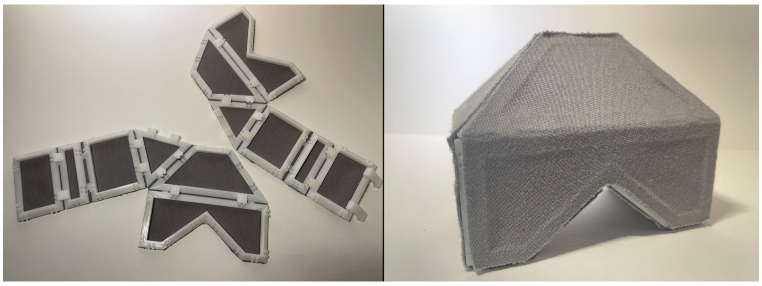

Figure 7.1: The finished test object. The used connector is the 2 row nub connector. On the left side you can see the model in its flat state with the bridges already applied. On the right side you can see the finished assembled model.

7.2 Results of the User Study

In the following section, we will focus on the user study evaluation. Eight people participated in the user. Each participant needed between 1 hour and 1.5 hours for the complete study. We did not see major differences between participants in the time spent on the various tasks. Of the eight participants, three were female, five were male and the ages were distributed from 20 years to 26 years (mean = 23.25 and std. = 1.920). The majority stated that they have had no or only little experience with 3D-modelling or 3D-puzzles, but most people had experience with crafting.

No problems with assembly itself, without considering connectors

The participants had no problem in seeing how the flat model should be assembled to the 3D state. The object consisted of two islands, as it did not fit the print bed in one piece. For the first assembly, the participants had to rate how easy it was to find the right orientation to put the two islands together. Not a single person had difficulties with this step. Nearly everyone stated that it was clear where the concave and obtuse bridge pieces had to be put.

Assembly with 1 row nubs became better over time

Figure 7.2 shows the results of the assembly of the model with the different connectors. The connectors which allow the easiest assembly are the vertical slat and 2 row nub connectors. The assembly of the 1 row nub connector was rated as hard by the first three people, though most of the

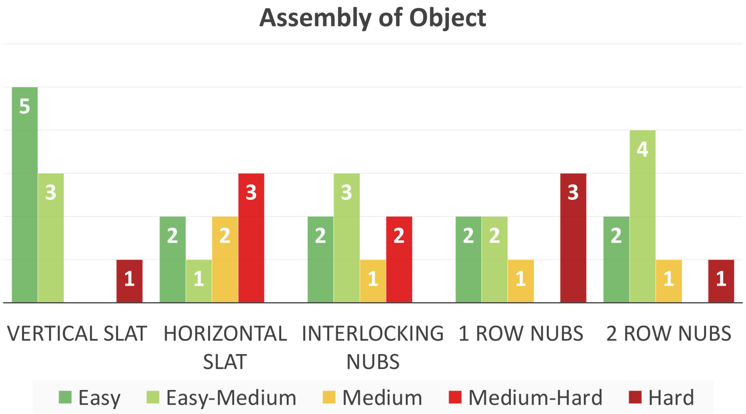

Figure 7.2: Evaluation of the ease of assembly with the different connectors

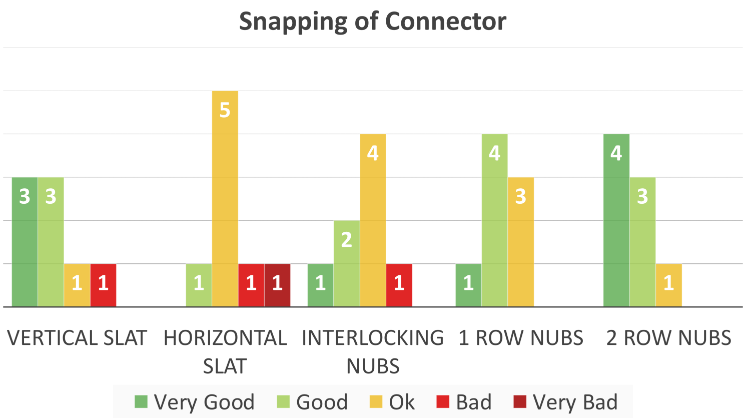

Figure 7.3: Evaluation of the snapping during the assembly of the different connectors

following participants (4/5) rated it as *easy* or *easy-medium*.

Figure 7.3 illustrates the ratings of the snapping of the various connectors. The results show that most connectors did a good job on this part. The horizontal slat connector had the worst rating of all tested connectors for this factor. The 1 row nub and 2 row nub connector were very hard to assemble at the beginning of the study, but gave an acoustic feedback when they finally snapped together.

Participants loved sound feedback when connector snapped together

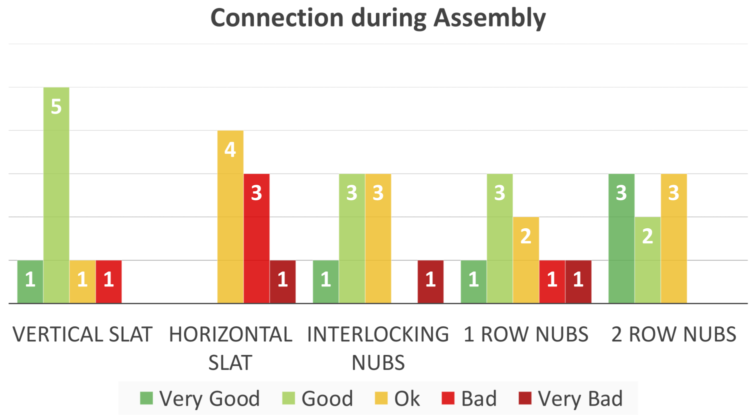

Figure 7.4: Evaluation of the connection strength during the assembly

Connection of horizontal slat become quickly worse

The next important point of the study was to examine which connector gave the best strength during the assembly of the object. The results of this step can be seen in figure 7.4. Again the horizontal slat connector performed the worst. As already mentioned before, the 1 row nub connector was hard to apply in the beginning. This resulted in the participants not being able to assemble the connections on some of the edges, until the connector was galled. The rest of the connectors performed well in this step. For the horizontal slat connector, the bridges came loose very easily, even at the beginning of the study. After assembling the object, some bridges even fell off on the inside of the model.

Sturdiness of horizontal slat was very bad

After the assembly was done, the participants had to rate how sturdy the object turned out to be. Every connector achieved good results except for the horizontal slat connector. It was rated *very bad* by one quarter of the participants. The vertical slat and the interlocking nubs were rated *very good* by three quarters of the people, followed by the two row nub connector. The complete results of this step can be found in figure 7.5. For the interlocking nubs, it was mentioned that the model was very loose during the assembly, but became really sturdy as soon as the assembly was completed: "While assembling the object the connectors didn't seem sturdy at all, but now that it is put together the model is very stable" (P4).

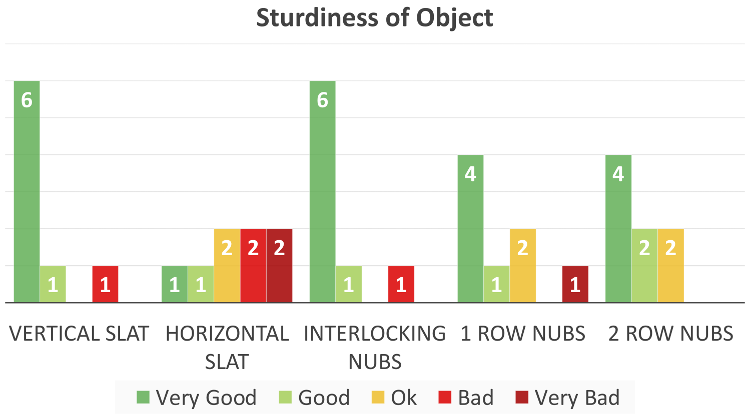

Figure 7.5: Evaluation of the sturdiness after the assembly

After the sturdiness test, the participants had to disassemble the object again. For the first disassembly, the people had to rate whether it was clear how to disassemble it. All stated that this was *very easy*. The participants also had to rate how difficult it was to break apart the connectors. The results of this question can be found in figure 7.6. Every connector came loose easily, except for the 2 row nub connector, which held together tightly and was rated as the hardest to break apart. One participant (P1) mentioned that the interlocking nub bridges were ”tricky to remove”. This is due to the fact that the bridge cannot be pulled out straight upwards but needs to be removed in an angled fashion. To make this step easier, the participants had to pull the faces apart. One side of one connector pair broke off because of the pulling. During the disassembly of the model with the horizontal slats, the bridges often flew away while pulling the connected faces apart.

2 row nubs did not come lose easily at beginning

Horizontal slat bridges flew away on disassembly

The best rated connectors were the vertical slat connector as well as the 2 row nub connector. The clear loser of the rating was the horizontal slat connector which was placed last by half of the people. The exact results can be found in figure 7.7. One participant (P2) even gave some explanations for his ranking. The participant mentioned that the vertical slat is an ”all-rounder”, the 2 row nubs give the best strength and the 1 row nubs give a bit less strength. In addition, it was said that the interlocking nubs are ”average, but

Best rated: vertical slat and 2 row nubs
Worst rated: horizontal slat

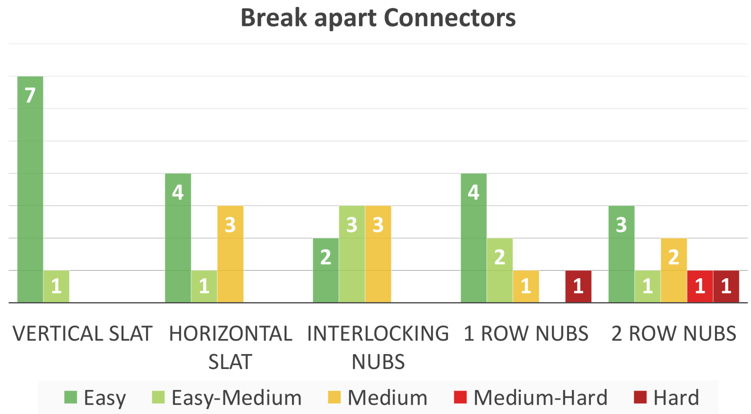

Figure 7.6: Evalution of how hard it was to break apart the different connectors

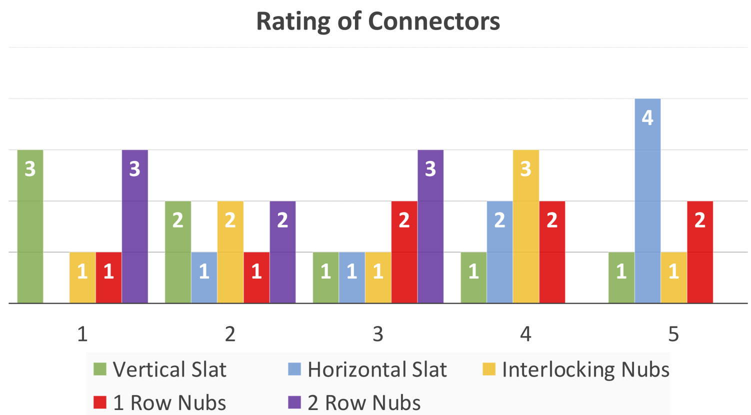

Figure 7.7: Rating of the connectors from 1 (best) to 5 (worst) of the different connectors

not in a good way" and that the horizontal slat is not strong at all. Overall though, the results are not unambiguous, as this seems to rely mostly on personal preference.

Not all bridges needed for assembly

Some general feedback that we received was that it was very difficult to use all provided bridge pieces. Some participants were able to use all bridges for some connectors, but this was not consistent and took a lot of time to achieve. We noticed that the pieces that could not be used were mostly the concave bridges and four big angle bridges which should have been used to connect the open edges of the roof.

The participants also enjoyed the snapping sounds the connectors made during the assembly, which was the case for every connector except the interlocking nub connector.

7.3 Discussion

This section will show the positive outcomes, as well as some problems, that we had with the different connectors during the preparation of the study and the study itself. In a next step, we demonstrate possible different applications of the connectors.

The connector pieces were not precise enough for very small angles, as the top surfaces were too stair-like. Therefore, we could not print the object with a homogeneous layer height, but had to use variable layer height to refine the precision where it was needed. This led to us not being able to save any printing time.

Concerning filament, we were able to save a lot of material on the missing infill and on the empty surfaces.

The interlocking nubs add a big gap between the edges of a face, so it would be good to use those only on edges, where the textile is not cut in between. As already mentioned before in section 7.2, one nub pair broke off during the disassembly. This is due to the fact that this connector has a more fragile nature than the other connectors and one has to find the right angle to pull bridges out.

Interlocking nubs can break on disassembly

The two other nub connectors have very tight tolerances at the beginning, so the first few assemblies are tough to complete successfully. After a few people had assembled/disassembled this connector and wore it out, it worked great.

Tight tolerances at beginning for 1 & 2 row nub connector

The horizontal nub connector has the problem during disassembly that the strength is concentrated along the angled

Strength at disassembly of horizontal slat concentrated along angled edges

edges, resulting in the connector being worn out quickly. This makes the disassembly tricky at the beginning, as the bridges tend to fly out. In addition, to the bridges flying out, the connector itself is worn out very quickly and the disassembly can even break small parts of the female side.

Ideally last closed face should not have bridge pieces

During the preparation of the study and also during the study itself, we noticed that not all bridge pieces are required to assemble a sturdy object. It was also very hard to effectively use all bridge pieces. We concluded that in order to use all bridges, the last face which has to be closed ideally has no bridges on the edges. In addition, concave bridges should not be on open edges but always on the inside of an island. The bridges are often not needed as the angle is given by the surrounding faces.

Sound feedback helps assembly

The sound feedback on assembly when the connector snapped together gave the people the assurance that it was correctly placed and secured.

Lastly, we want to present some applications for the different connectors. As there is no restriction to only use one connector for the complete model, a combination of the different versions allows to make use of the different strengths.

Combination of connectors on bridges to make assembly easier

The bridge pieces could benefit from a combination of a vertical slat and a 2 row nub connector. With this technique for the assembly, the bridges could be placed on the nub side in advance as this connector will hold the bridge part tightly. The vertical slat would additionally allow an easy assembly and disassembly for the other side of the edge.

1 row nubs for thinner edges

If only a small amount of space is available for an edge, one can profit of the small size of the one row nub connector. The width of this connector does not require much more than the diameter of the nub, while still allowing a lot of strength, according to section 7.2.

Last closed face should use easy to assemble connector

To ease the assembly and disassembly of a model, the last face which should be closed can use a different set of connectors which does not require a lot of force for assembly.

The first participants of the user study mentioned that the 1 row or 2 row nub connectors were hard to assemble. So these cannot be considered for this application. One of the slat connectors would probably the best choice for this part. Having an easily closable last face assures that the required force does not tear apart the object on the final step.

Chapter 8

Summary and future work

Last but not least, we present a short summary of the thesis and its contributions to the project Fabric Faces. This will be followed by what future studies will still have to work on and what could be additionally interesting to look at.

8.1 Summary and contributions

In this thesis, we developed a library of connectors that can be used for assembling 3D printed objects. All designed connectors were produced with Autodesk Fusion 360 and printed with the Prusa Mini after being sliced with PrusaSlicer. A lot of studies suggested that PLA gives the best results to print on textile, so this was our filament of choice. We also tried to print onto textile, but here some more studies are needed.

The designed connectors can be divided into two families, the slat connectors and the nub connectors. For each of the two families, we designed three versions. For the slat connector we constructed the vertical, sloped and horizontal slat. The sloped slat could already be sorted out right from the beginning, as our pretests immediately showed that this

2 families of connectors, slats and nubs, with each 3 designed connectors

Bridges for angles that are to big to print

Important parameters for automated model creation

version could not handle angles bigger than 70°. The nub connectors we designed are the interlocking nub connector and the one row, as well as the two row nub connectors. The connectors only gave good results up to 130°. For this problem we introduced two bridges that add an angle of 110° (big angles), and 250° (small angles) a printed connection. The big angle bridge is used from 120° up to 250° and the concave bridge from 250° to the full 360°. While creating the connectors, we kept record of all of the important parameters that were essential for the later object creation. Those parameters were the extra space, the taper angle, the female connector size and the separation distance for faces of flattened models. They will be crucial for the automated model creation using software.

Textile tests gave good adhesion but much warping

Additionally to the connectors, we also tested the ability to print onto textile. For testing purposes we used three different shapes, a line a square and a random shape. The adhesion force was then tested with simple peel and shear tests using a spring scale. Nearly all tests exceeded the maximum force of the measuring device, except for the peel test for the random shape, where overall bad results were achieved. We chose the *Cotton Jersey* for the continuation of our study, as this textile offered the least warping. However, the warping was still exceeding the acceptable amount for assembly of our first test objects. In order to be able to conduct our user study to test out the connectors, we proceeded by gluing the textile to the test object.

Save a lot of filament on faces and infill

Clicking noise gives important feedback on assembly

For our test object we found out that we saved approximately 45% filament, but we were not able to save time in printing. In the user study, we observed that there were no major problems with assembly, though it was difficult to use all of the bridges for the object. At first, the 1 row nub connector was hard to assemble but this was ameliorated after it had been worn out a bit. Most of the designed connectors made a clicking noise which assured the participants that the connector snapped together properly. Looking at strength, every connector had satisfying results, with the exception of the horizontal slat. Said connector wore out very quickly and only allowed a strong connection during the first few assemblies. The sturdiness of the connectors was also good for every connector, except for the horizontal slat. The 2 row nubs connector was very hard to take apart for most of the study. The overall best rated connectors were the vertical slat and the one and two row nubs. During the user study, we also found some problems with the connectors, like for example that the interlocking nubs can break on disassembly and that the other nub connectors are very hard to assemble at the beginning. As one is not limited to only using one sort of connectors in a model, it is possible to use the strengths of the different connectors for different applications.

8.2 Future work

In the future, one could investigate how to make the connectors smaller, as all connectors, beside the 1 row nub connector, need a face of 5mm in width at the moment. The problem here is to achieve a good connection with a small surface. The connectors also wear out over time, which probably happens even faster with smaller connectors. Another problem that has to be examined is the warping problem while printing onto textile. The magnets and the double sided tape did not ensure enough adhesion to the build plate for them to prevent the print and the textile from lifting.

Investigate in decreasing size of connectors and warping problem on textile

A next step for this project will be to create software to automate the creation of an object using the Fabric Faces principle. The software will first need to simplify a model to reduce the number of faces, in order for the model to be laid out flat later on. The software will have to calculate the right spots for the folds and use the designed connectors and found parameters of this work. Some more work is also needed to find out how to generate the islands of an flattened object to make assembly even possible. The steps after the printing could also be simplified in the future, as cutting the textile by hand adds a huge part of post processing to the job. One solution for this would be to add a qr-code to the print. This code could be used to let a laser cutter identify the orientation of the print and to cut out the object. This project could additionally profit from multi colour printing to mark how and which parts have to

Software to automate the object creation process

Simplify the cutting process

Multi colour print to mark edges for multiple islands

be connected to each other, in case the constructed model consists of multiple islands. If there are too many parts, it would be possible that it is not obvious to the user where which part belongs.

It could also be very interesting to somehow include self assembly, as already shown in section 2.1, for difficult-to-reach parts on a flattened object.

Multiple angles for one connector

To make interaction with a Fabric Faces object possible, connectors that allow multiple angles could bring some benefits. As an example, we could imagine some faces which act as a button with two states. When pressed, the button locks in the second position and when pulled, it locks back into the first position.

Appendix A

Informed Consent Form

Informed Consent Form

Fabric Faces Library – User Study

Principle investigator: Sam Mattiussi
Email: sam.mattiussi@rwth-aachen.de

Purpose: The goal of this study is to investigate the influence of different connector designs on the sturdiness of a 3-dimensional object constructed from 2-dimensional parts. Furthermore, we want to investigate the influence of the connectors on the assembly and disassembly of the object. The data collected during this study will help with connector design and guide decisions on implementation and usage in the future.

Procedure: Participation in this study involves assembly and disassembly of five objects, each with a different connector. Afterwards, a questionnaire is handed to the participant to rate the completed steps. Each step will be timed.

Risk/Discomfort: Even though the study is expected to last no longer than one hour, you may become fatigued during the course of your participation in the study. Feel free to take as many breaks as necessary during the study. There are no risks associated with participation in the study. Should completion of the task become distressing to you, it will be terminated immediately.

Confidentiality: All information collected during the study period will be kept strictly confidential. You will be identified only through identification numbers and background information you divulge in publications or reports. If you agree to join this study, please sign your name below.

Addendums: Participation in this study is voluntary. You are free to withdraw or discontinue the participation. Participation in this study will involve no cost to you.

- ▢ I have read and understood the information on this form.
- ▢ I have had the information on this form explained to me.

________________________	________________________	____________
Participant’s Name	Participants Signature	Date
	________________________	____________
	Principle Investigator	Date

Appendix B

User Study Questionnaire

Fabric Faces User-Study

Participant ID: ______________ Age: __________ Gender: ______________

	Never	Once	A few times a year	Weekly	Daily
How often do you do 3D-modeling?	☐	☐	☐	☐	☐
How often do you do 3D-puzzles	☐	☐	☐	☐	☐
How often do you do craft?	☐	☐	☐	☐	☐

1 ______________

Time: ______________

	Easy		Medium		Hard
Assembly					
How difficult was it to go from 2D to 3D?	☐	☐	☐	☐	☐
How difficult was it to find the correct position for the part?	☐	☐	☐	☐	☐
Was it clear where to put the additional parts?	☐	☐	☐	☐	☐
How easy was the assembly of the object?	☐	☐	☐	☐	☐
	Very Bad		**Ok**		**Very Good**
Connector					
How do you rate the snapping of the connector?	☐	☐	☐	☐	☐
How well was the connection during the assembly?	☐	☐	☐	☐	☐
How sturdy was the assembled object?	☐	☐	☐	☐	☐
	Easy		**Medium**		**Hard**
Disassembly					
Was it clear how the object had to be disassembled?	☐	☐	☐	☐	☐
How difficult was it to break apart the connectors?	☐	☐	☐	☐	☐

Additional Notes:

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2 ______________________

Time: ______________

	Easy		Medium		Hard
Assembly					
How easy was the assembly of the object?	☐	☐	☐	☐	☐
	Very Bad		**Ok**		**Very Good**
Connector					
How do you rate the snapping of the connector?	☐	☐	☐	☐	☐
How well was the connection during the assembly?	☐	☐	☐	☐	☐
How sturdy was the assembled object?	☐	☐	☐	☐	☐
	Easy		**Medium**		**Hard**
Disassembly					
How difficult was it to break apart the connectors?	☐	☐	☐	☐	☐

Additional Notes:

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3 ______________________

Time: ______________

	Easy		Medium		Hard
Assembly					
How easy was the assembly of the object?	☐	☐	☐	☐	☐
	Very Bad		**Ok**		**Very Good**
Connector					
How do you rate the snapping of the connector?	☐	☐	☐	☐	☐
How well was the connection during the assembly?	☐	☐	☐	☐	☐
How sturdy was the assembled object?	☐	☐	☐	☐	☐
	Easy		**Medium**		**Hard**
Disassembly					
How difficult was it to break apart the connectors?	☐	☐	☐	☐	☐

Additional Notes:

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____

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4 ____________________

Time: ________________

	Easy		**Medium**		**Hard**
Assembly					
How easy was the assembly of the object?	☐	☐	☐	☐	☐
	Very Bad		**Ok**		**Very Good**
Connector					
How do you rate the snapping of the connector?	☐	☐	☐	☐	☐
How well was the connection during the assembly?	☐	☐	☐	☐	☐
How sturdy was the assembled object?	☐	☐	☐	☐	☐
	Easy		**Medium**		**Hard**
Disassembly					
How difficult was it to break apart the connectors?	☐	☐	☐	☐	☐

Additional Notes:

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5 ____________________

Time: ________________

	Easy		**Medium**		**Hard**
Assembly					
How easy was the assembly of the object?	☐	☐	☐	☐	☐
	Very Bad		**Ok**		**Very Good**
Connector					
How do you rate the snapping of the connector?	☐	☐	☐	☐	☐
How well was the connection during the assembly?	☐	☐	☐	☐	☐
How sturdy was the assembled object?	☐	☐	☐	☐	☐
	Easy		**Medium**		**Hard**
Disassembly					
How difficult was it to break apart the connectors?	☐	☐	☐	☐	☐

Additional Notes:

Rate the connectors from 1 to 5:

Vertical Slat	
Horizontal Slat	
Interlocking Nubs	
Nubs 1 Row	
Nubs 2 Rows	

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Typeset March 22, 2021