“You wouldn’t download a T-shirt” - 3D printing of everyday clothing at home

Lance Roozen

Creative Technology Bachelor project
Supervisor: Angelika Mader
Academic year 2016-2017
University of Twente

Introduction

3D printing offers a lot of potential in many industries, but the possibilities it has in the fashion industry are still largely unexplored. There are a number of scientific articles that modestly explore the possibilities of combining 3D printing and fabric, but the practise of 3D printing clothing is still really new, with the first fully 3D printed clothing item being as recent as 2013 (Duann, 2014). Since then many other haute couture artists have made use of 3D printing in their work, but the clothing they make is often more of an art piece meant to be displayed on a catwalk than a piece of clothing.

So, the first reason why it was decided to work with 3D printed clothing is because of the desire to bring this brand new fashion design technique into the homes of regular people. It is common for people to make their own clothes with traditional fabrics, and a good commercial sewing machine costs about the same as a small commercially available 3D printer. The only thing preventing individual consumers from printing their own outfits is that we simply do not know how they could yet. Finding a way to print textiles in one’s own home is pushing the boundaries of a still new technology.

The second reason is that 3D printing offers huge possibilities in reducing waste in the fashion industry. Because it works by adding layers of material rather than cutting away material to get the desired shape, 3D printing produces far less waste - possibly even none, assuming failed prints can be melted again to be recycled. The possibility of printing clothes exactly to fit the wearer further reduces waste, since no item contains more material than needed. 3D printing is also an on-demand service, so there is no need to store the products before they are sold, and there is little to no manual labour required to assemble the piece which removes the need for cheap (and often highly unethical) labour to do this.

The main things currently standing in the way of ready-to-wear 3D printed fashion are the limitations of the technique itself, and the still relatively high price and low availability of a 3D printer and the material it works with as opposed to a sewing machine and fabric. It is the limitations of the medium itself that will be attempted to overcome here in order to develop a method that can be used to print clothing similar in use to what can be found in your average clothing store, rather than on your average haute couture catwalk.

Ideation

Research question

The research question is as follows: “**What are some possibilities, using 3D printing methods that are available commercially, to create an item of clothing that is both visually appealing and suitable for daily wear?**” “Suitable for daily wear” here would be items that someone would wear to, for example, the supermarket.

During the course of this process the following subquestions will be answered:

1. What are the requirements for wearability?
2. What techniques for 3D printing textiles, preferably using commonly available 3D printers, currently exist?
3. How can these techniques be used to create a full item of clothing, in a way which can be easily copied?

The goal is to explore techniques that will allow 3D printing to make its way from high fashion shows into the wardrobe of the average person.

Related work

3D printing techniques

Although scientific research on the topic of 3D printed fashion is rare, there are still a handful of interesting publications concerning both printing fabrics, and printing *on* fabrics. In this section the word “technique” is used to mean the ways in which 3D printers can be used to print textiles. The word “method” is used to refer to the types of machines themselves.

The two most common types of 3D printers are Fused Deposition Modelling (FDM), which melts a filament down and deposits it into layers that build up the desired shape, and Selective Laser Sintering (SLS), which uses a laser to melt layers of powder together into the desired shape. There also exist more highly specialised printers. FDM printing is the cheapest and most widely available method, and it is also the type of printer that has been experimented with the most in terms of creating fabrics. 6 out of the 11 examined papers made use of an FDM printer.

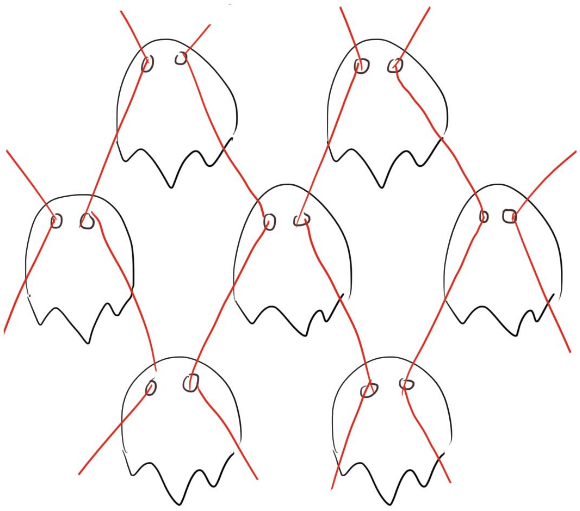
It is possible to create structures that are somewhat flexible using an FDM printer (Melkinova, 2014). By using either soft PLA or Lay Tekks filament (which seems to be no longer available), and printing in lace-like patterns, a flat piece of material that can be bent around the shape of the body can be made. Special care has to be taken in designing the structure, because without sufficient support structures in the model the end product will break while still being printed.

The best results with this type of printer seem to be when it is used to print on top of traditional fabrics, rather than to create a fabric from scratch, as these are the results obtained in every other examined paper that discussed FDM printing. This approach is further divided into two specific approaches: sandwiching a mesh fabric between layers of printed material (Sabantina et al., 2015; Sensoree, 2017), or printing directly on top of the fabric (Santagar et al., 2017; Korger et al., 2016; Grimmelsmann, 2016; Pei, 2015). For the first technique, the first few layers of the model are printed, then the mesh fabric is placed on top, and then the remaining layers are printed. Due to the porous nature of the fabric, its fibres are encased in the filament and the printed shape is securely attached (Sabantina et al., 2015). For the second technique, the results depend a lot on the combination of what fabric is printed on, what kind of filament is used, and at what temperature the printing is done. However, the results are largely positive. The filament attaches firmly to common fabrics such as cotton (Korger et al., 2016; Pei, 2015) and knitted wool (Grimmelsmann, 2016). The fabric also does not warp, and remains flexible and stretchable as long as only a small part of it is printed on.

With an SLS printer, it is possible to print a knitted structure and create a fabric that way (Beecroft, 2016; Vanderploeg et al, 2016). The resulting fabric is flexible and looks somewhat similar to chainmail. It is also possible to print the structure at a small scale, giving it increased flexibility and making it less see-through at the cost of decreased sturdiness. Printing knitted structures like this is not possible with an FDM printer due to the need for support structures when printing with an FDM printer, which makes creating a knitted structure at a size that is useable as a fabric effectively impossible (Melkinova et al., 2014).

In addition to these two common types of 3D printers, there exist more highly specialised printers that can be used for the creation of fabrics. First, there is the printer made by Hudson (2014) and developed further in Peng et al. (2015), which uses a felting method to pull loose fibers together into a specific shape and create 3D objects that are soft and flexible. The further developed version laser-cuts the shape of the object out of several layers of fabric and then attaches them together to achieve the same effect, but more accurate. Second, there is the electrospinning method developed by White et al. (2015). A mixture of fabric fibres is deposited onto a mold to create a material that behaves much like traditional fabric in terms of flexibility and texture, although it is not as strong as traditional fabrics.

The possibilities of 3D printed fabrics have also been explored in own earlier work. In this project, a flexible filament was used with an FDM printer to print a number of scale-like shapes (fig. 1), which would be sewn together to form a flexible structure as shown in figure 2. There were several problems encountered with this project however. The printer did not take well to the flexible filament and would often produce incomplete prints. The product also required a lot of complex assembly to make a fabric, and was very bulky.



Left: Figure 1, the printed scales. Right: Figure 2, the pattern in which the scales connect.

Wearability

None of the articles attempting to develop a 3D printed textile explicitly detailed just what definition of “wearability” they operate on. A number of underlying assumptions were present and identifiable however. First, the full garment must be flexible around joints in order for the wearer to be able to move around in it (Vanderploeg et al., 2016; Beecroft, 2016; White et al., 2015; Pei, 2015). Second, the material the garment is made of cannot be rough or coarse against the skin (Vanderploeg et al., 2016; White et al., 2015). Third, the fabric must not be able to tear easily (Sabantina et al., 2015; Pei, 2015). Each of these assumptions is likely rooted in the authors’ own experience of wearing clothing every day and what they do or do not find comfortable in a specific garment, causing them to forget to acknowledge these assumptions.

The definition of “wearability” found is very basic, but still useable. Flexibility around joints, not being rough against the skin, and not tearing easily form a suitable set of base qualities the final garment needs to have in order to be wearable. Another criteria that is not mentioned by any of the examined sources but should still be considered is that the garment needs to fit the measurements of the wearer. A garment that is too loose or too tight is uncomfortable, and thus cannot be said to be wearable. The final definition of wearability that will be taken from this is that the garment:

- needs to be flexible around joints
- must not rough against the skin
- must not tear easily
- must fit the measurements of the wearer.

This is considered enough to judge the product in its early stages, and more complex definitions of wearability can be brought in to examine any later stages.

Fashion design

Just because there is not a lot of scientific literature on the matter does not mean not a lot has been done yet in terms of 3D printed fashion. The first fully 3D printed item of clothing was Dita Von Teese's dress, designed and made by Michael Schmidt and Francis Bitonti (Duann, 2014). It consists of a large number of articulated components, printed in 17 pieces, which when assembled form a flowing, see-through dress, depicted in figure 4. Several other designers have taken a similar approach, creating designs with holes in them in order to allow for flexibility when worn. Danit Peleg (2014) made the collection shown in figure 5, and the blue dress in figure 3 is by design group threeASFOUR (Armstrong, 2016). In addition to the holes in the structure, these two works are also made with a flexible material in order to allow for them to bend around the body.

Left: Figure 3, photo taken from Armstrong (2016). Top right: Figure 4, photo taken from Duann (2014). Bottom right: Figure 5, photo taken from Peleg (2014)

The design studio Nervous System has also produced a number of 3D printed dresses, with their second model, the Kinematic Petals Dress, eliminating the holes featured in many other designs by covering them with petal-like shapes. Both the Kinematics Dress (fig. 6) and the Kinematic Petals Dress (fig. 7) are similar to the Dita von Teese dress in that they are made of a large number of interlocking pieces, but these are impressively enough printed in one go by folding the model so that it fits into the printer in its entirety. (Nervous System, 2014, 2016). From this it can be inferred that an SLS printer or similar was used for these, because an FDM printer would need support structures to print multiple pieces above each other, which would interfere with the design.

Left: Figure 6, photo taken from Nervous System (2014). Right: Figure 7, photo taken from Nervous System (2016)

There are different applications for 3D printing beyond dresses and tops too. For example, fashion student Jess Haughton has used 3D printing to create seamless lace lingerie that fits the wearer perfectly (Nottingham Trent University, 2016). Shoes are another popular item for fashion designers to 3D print, such as the Myth shoes (Continuum, 2014). Advances in 3D printed shoes seem to be much faster than for other types of clothing too, with Adidas recently revealing plans to start mass-producing 3D printed shoes (Michalska & Thomasson, 2017). This likely has to do with how shoes require far less flexibility than other garments, making it easier to use a 3D printer for them.

Top: Figure 8, 3D printed shoes by design studio Continuum, taken from Continuum (2014). Left: Figure 9, 3D printed lingerie, photo taken from Nottingham Trent University (2016). Right: Figure 10, Adidas Futurecraft shoe, photo taken from Michalksa and Thomasson (2017)

Interviews

Contemporary artist Viola van Alphen was contacted for recommendations on related work. As the organiser of the art festival GOGBOT she has experience and contacts in a wide range of technological art, and she was kind enough to point towards the work of several fashion designers who have worked with 3D printing.

The artists that were contacted are Kristin Neidlinger, Maartje Dijkstra, and Iris van Herpen. Each of these have created impressive 3D printed garments, albeit far more on the artistic than the wearable side. Unfortunately, out of these, only Kristin Neidlinger was available for an interview. Fabric developer and fashion designer Hellen van Rees was contacted separately. She had expressed great enthusiasm for this project and also agreed to an interview. The full interviews are in the appendixes.

The main goal of these interviews was to gain insight in the design process behind 3D printed fashion, and the role it has compared to other fashion techniques to a professional fashion designer. Most of the things Neidlinger and Van Rees said are in line with things concluded from the abovementioned research, such as the limits in flexibility of the material used in 3D printing, and the appeal of the different shapes it can potentially be used to make. One interesting reveal however is that while the precise sizing possible through 3D printing is one of its strengths, it can also be a pitfall when the size is wrong and a print has to be discarded because it doesn’t fit. Van Rees also brought up the surface texture of the material as a factor to consider in the overall comfort of the product.

Contact with Van Rees was maintained throughout the design process.

Initial requirements

These are the principles that will guide the design of the final product, as decided based on researching the current state of the art. They are all chosen with the ultimate goal of “making ordinary clothing using a commonly available 3D printer” in mind.

For the sake of wearability:

The fabric must be flexible enough to comfortably move in.
The fabric must not be rough against the skin.
The fabric must not tear easily.
The final garment must fit the measurements of the wearer.
The final garment should not be see-through.

These requirements are based on personal experience with wearing clothing every day, as well as the assumptions on wearability identified in the examined literature. The final point on this list comes from the observation that a lot of 3D printed fashion incorporates a lot of holes in the design. If one is to create a garment suitable for everyday wear however, it cannot be see-through, because that would make it indecent unless something is worn underneath.

For the sake of accessibility:

The product must be possible to make with a (small) FDM printer
The product must be simple to assemble.
The product ideally does not require hard to obtain materials to create.

These requirements are determined based on wanting to create a product that differs from those that already exist. A lot of impressive 3D printed fashion already exists, but very little of it fulfills all three requirements. It either uses a type of printer that is not as accessible as the FDM printer, or if it does, it is difficult to assemble.

Specification and realisation

The realisation process involved a number of very quick and small iterations in order to arrive at a useable product, with each iteration attempting to answer a question that determines what the next step will be.

Goals

Before starting the realisation process, two goals are set: an optimistic and a pessimistic one. This gives a clear baseline to work towards and leaves room to account for unexpected developments.

The optimistic goal is to create a single item of clothing that adheres to all the criteria specified above.
The pessimistic goal is to create a single, roughly 30cm by 20cm swath of fabric that adheres to the majority of the criteria specified above, or shows promise of adhering to these criteria in later iterations.

Step 1

Starting point
This iteration starts from scratch

Goal/question
What are some shapes that will, upon being connected, make for a flexible and visually appealing structure?

Experiment
Several shape patterns were drawn on cardboard. These were then cut out and connected with tape, and tested for flexibility by bending across the cut. Placing the piece on the inside of the elbow and then bending the arm is used as a measure of how well the structure would do in a piece of clothing.

The main inspiration for this step are the Kinematics Dress and the Kinematics Petal Dress. Since the printer that will be used is small, using several small connected shapes such as the ones that compose the Kinematics Dress is vastly preferable to the much larger pieces that compose the clothes made by Peleg and threeASFOUR.

Observation
The hexagon pattern is completely inflexible. The squares are flexible, but limited by having only two axises to bend across. Both triangle patterns are more flexible than the squares, but the green triangles bend in such a way that it obstructs their own movement: once bent in one direction, it is hard for it to bend across another axis.

Conclusion
The number of axes the structure can bend across has a big influence on how flexible the structure is. Although more axes equalling more flexibility is the intuitive conclusion, it seems

that too many axes will cause the structure to obstruct itself. A pattern made of equal triangles that can bend in three directions shows itself to be the most flexible.

Pictures

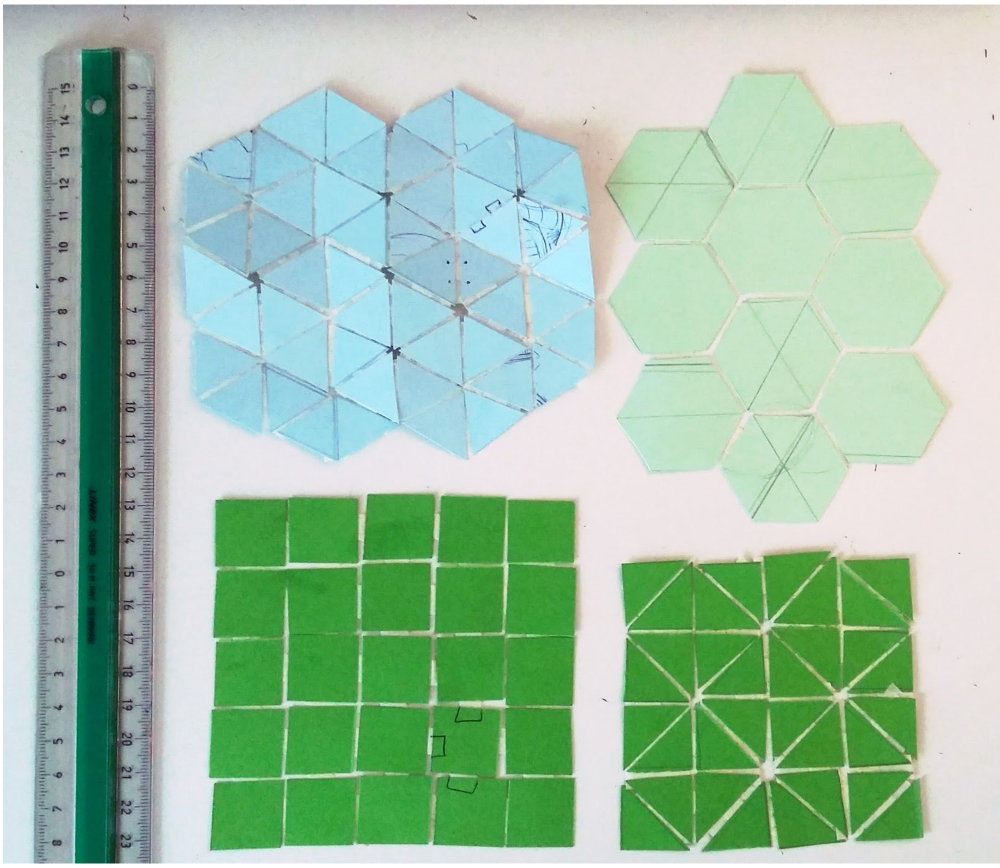


Figure 11, different patterns that were tested for flexibility. The top left pattern proved the most flexible.

Step 2

Starting point
At this point it is known that a pattern made of equal triangles is the most flexible. However, the basic geometric shapes are still somewhat boring to look at.

Goal/question
To make the patterns experimented with in the previous iteration more visually distinctive.

Experiment
Using the squares and triangles as a base, the shapes are expanded upon by making the edges curved. The curve is made sure to be the same on all edges so that the pieces will fit together. Again, the pieces are drawn onto coloured cardboard and then cut out and taped together.

Observation
Both patterns stay approximately as flexible as they were with straight edges. However, the visual effect of the pieces bending is more interesting because the curved edges stick out

when the piece is bent. The curved lines also create a more dynamic look even when the piece lays flat.

Conclusion
A triangle or square with curved edges makes for a visually interesting pattern that is also flexible. The triangles are more aesthetically pleasing based on personal preference. Since the triangle pattern had also shown itself to be more flexible in the previous step, this is the one that will be expanded upon in the following iterations.

Pictures

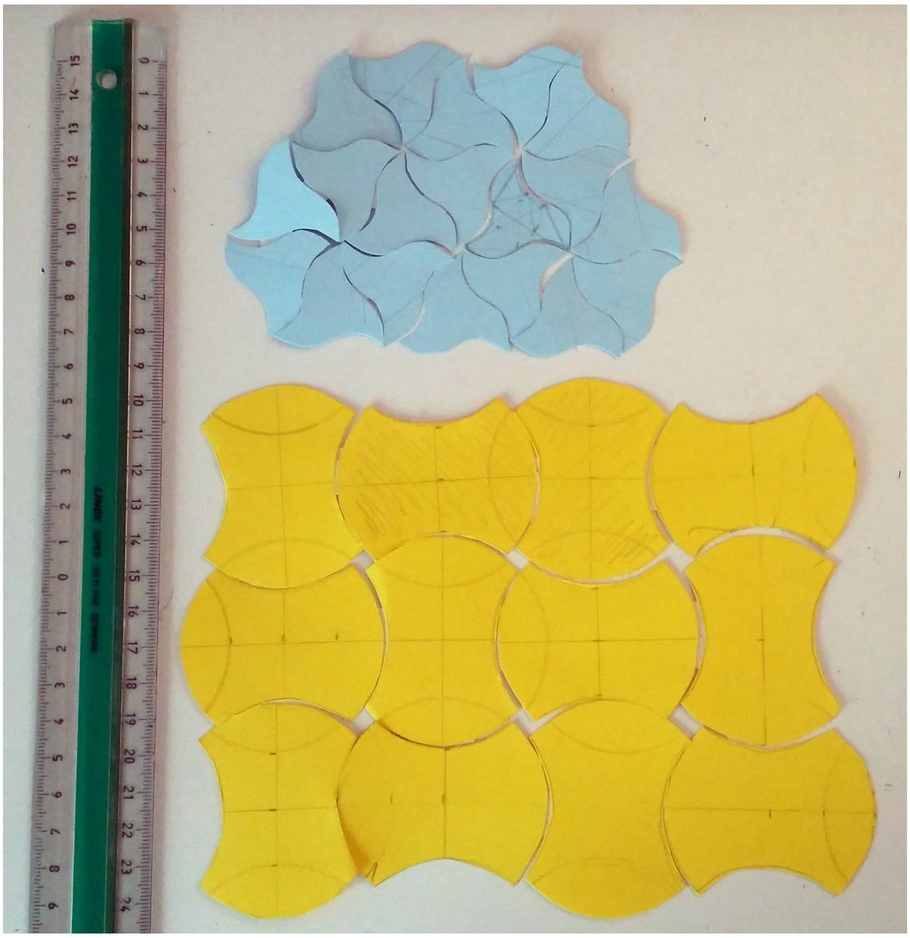


Figure 12, curved triangle and square patterns

Step 3

Starting point
A pattern consisting of triangles with curved edges

Goal/question
At which points must the pieces be connected in order to provide the best results?

Experiment
The triangle pattern was recreated in a vector format and cut out of cardboard using a laser cutter to obtain a number of pieces of absolute equal size. These were then connected using

needle and thread to sew them together. One set was connected at the middle of each edge, and the other at the far points, as shown in figure 13.

Observation
Both connection points appear roughly equally flexible. They create different effects however. The pattern connected at the middle points has the end points stick out far more than the one connected at the ends, creating a more rough look
The laser-cut patterns are less flexible than their hand-cut counterparts due to the thickness of the cardboard and how close together the pieces are. The thickness gets in the way of the pieces being able to move freely.

Conclusion
Because both pieces are somewhat rigid it is difficult to tell whether one connection point provides better flexibility than the other. If time allows, it would be worth the trouble attempting to test both again in a later step.

From the issue with the thickness of the pieces causing them to block each other from moving it becomes clear that either there should be more space between pieces, or the edges of the pieces should be rounded so that they do not obstruct each other. The rounded edges will be preferable because creating more distance between the pieces will make the fabric as a whole more see-through, which goes against the set requirements.

Pictures

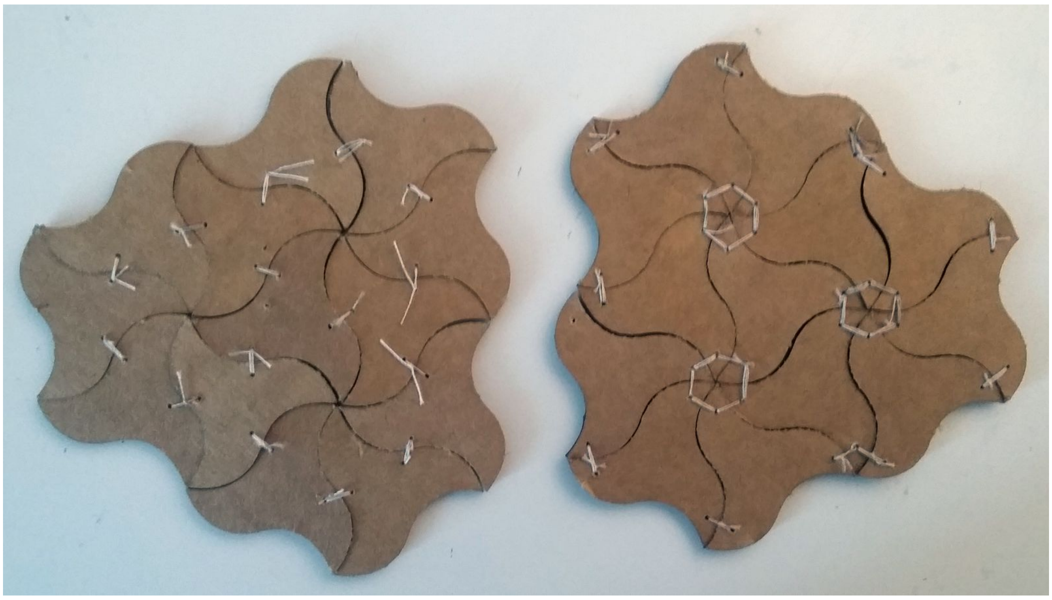


Figure 13, different connection points

Step 4

Hellen van Rees was shown the model while this step was in progress.

Starting point

A pattern consisting of triangles with curved edges, and the knowledge that the point at which they are connected does not seem to influence overall flexibility much

Goal/question

To create a method for the pieces to be connected that is possible for an FDM 3D printer to make.

Experiment

First, the curved triangle was recreated using the 3D modelling software Autodesk Maya. Although it was concluded earlier that the edges of the triangle need to be rounded in order for it to not obstruct its own movement, this is left for a later iteration for now so that all attention can be focused on developing the way the triangles connect. Then, a mechanism for connecting the triangles was modelled.

This mechanism makes use of a pin that is clicked into place in a hole, which should allow for free movement along a single axis. It is inspired by a combination of a side release belt buckle, and the connections found in children's building toys such as LEGO Mindstorms[1] and K'NEX[2].

Finally, the model was printed using an Ultimaker 2+ printer. The length of the triangle is approximately 4cm and kept consistent for every print.

Observation

The printer is capable of printing the pins on the side by means of support structures that are generated inside Cura, the program which processes the 3D models for printing. The pieces are sturdy and lightweight. Printing them takes a little less than an hour per piece.

While both the holes and the pins are printed correctly, they do not fit together. The protruding parts that the pins are attached to are too far apart, and even when fully bent towards each other the pins still stick out too much to click them into the slot.

Conclusion

The mechanism is possible to print, but needs some adjustments before it will work properly.

[1] https://www.lego.com/en-gb/mindstorms
[2] http://www.knex.com/

Pictures

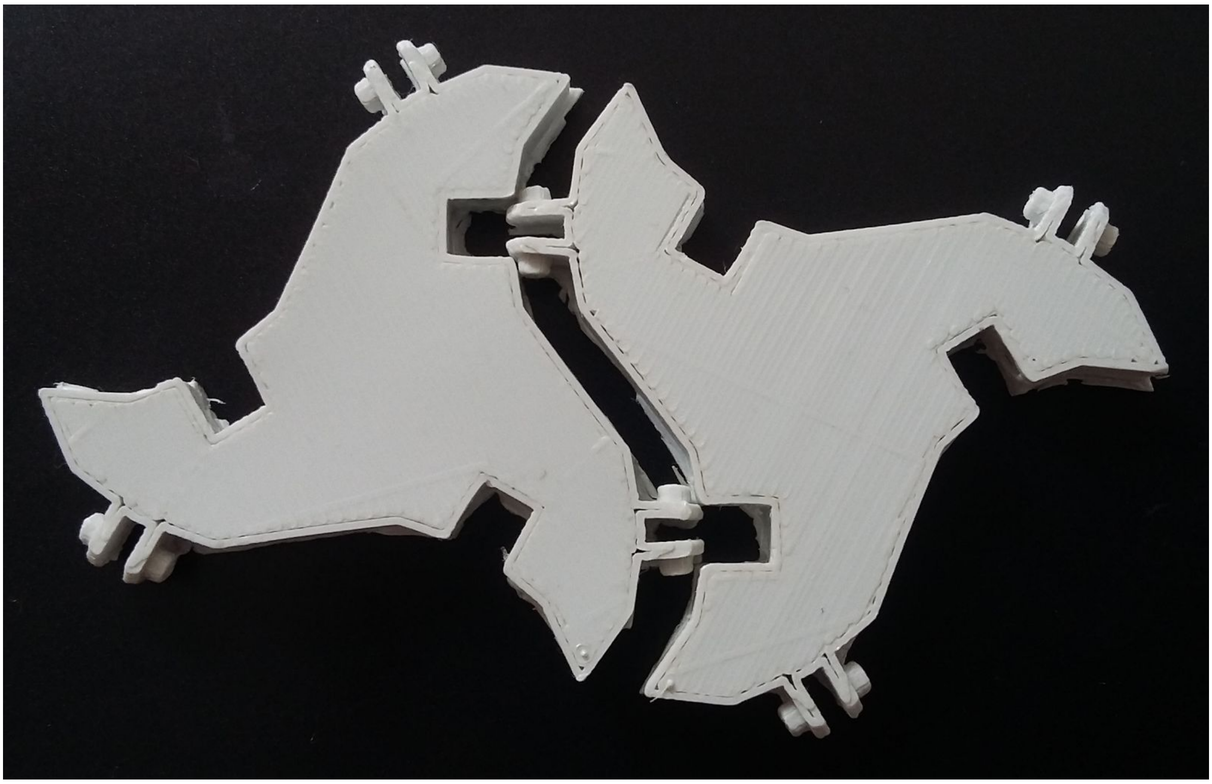


Figure 14, the mechanism cannot click into place

Step 5

Starting point
A 3D model of a curved triangle with a mechanism to connect multiple triangles to each other

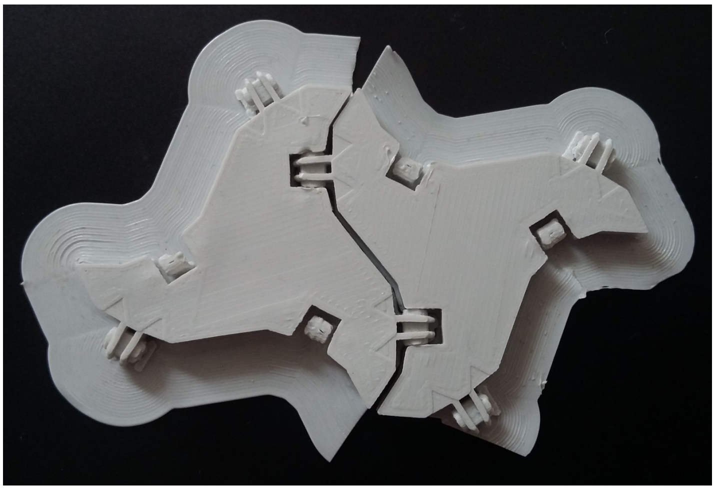
Goal/question
To adjust the model in such a way that the mechanism clicks together properly

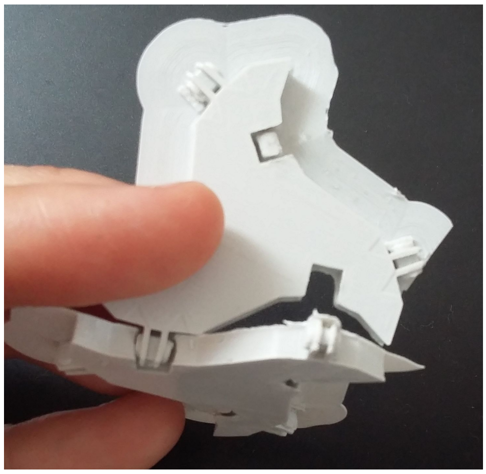
Experiment
The protruding pieces were moved closer together, and also made to point at each other a bit so they should bend towards each other more easily when clicked into place. The pins were made to stick out less and have a larger diameter. The holes were changed to match. Two of these triangles were printed.

Observation
The pieces now fit into each other, but do so too well. The pins don't actually click into the holes. In addition, trying to bend the pieces as they should revealed that, with the hinges placed as they are, they will block each other's movement.

Conclusion
The mechanism itself needs to be adjusted some more in order to click properly. It also needs to be placed elsewhere on the triangle if it is to actually move.

Pictures





Left: Figure 15, the pins do not click into the holes. Right: Figure 16, bending one hinge will dislodge the other

Step 6

Starting point
A 3D model of a curved triangle, with a faulty connection mechanism.

Goal/question
To adjust the attachment mechanism so that the triangles don’t obstruct their own movement

Experiment
The model was edited so that the triangles are connected at a single point on each edge. The pins and holes were placed on separate triangles, the one with the pins called “out” and the one with holes called “in”. Both of these were then printed once.

Observation
The edges of the triangles don’t align well with the mechanism. In order for it to click together, part of the triangles had to be cut off. The out triangle also doesn’t extend far enough to fit into the in part. The parts were printed with a piece of material between the out bits that is not there in the model, which had to be removed.

Conclusion
The parts need to be adjusted so that the edges and mechanism parts line up properly. Since the material between the out bits is not there in the model, some experimenting with the settings in Cura is also needed to avoid those.

Pictures

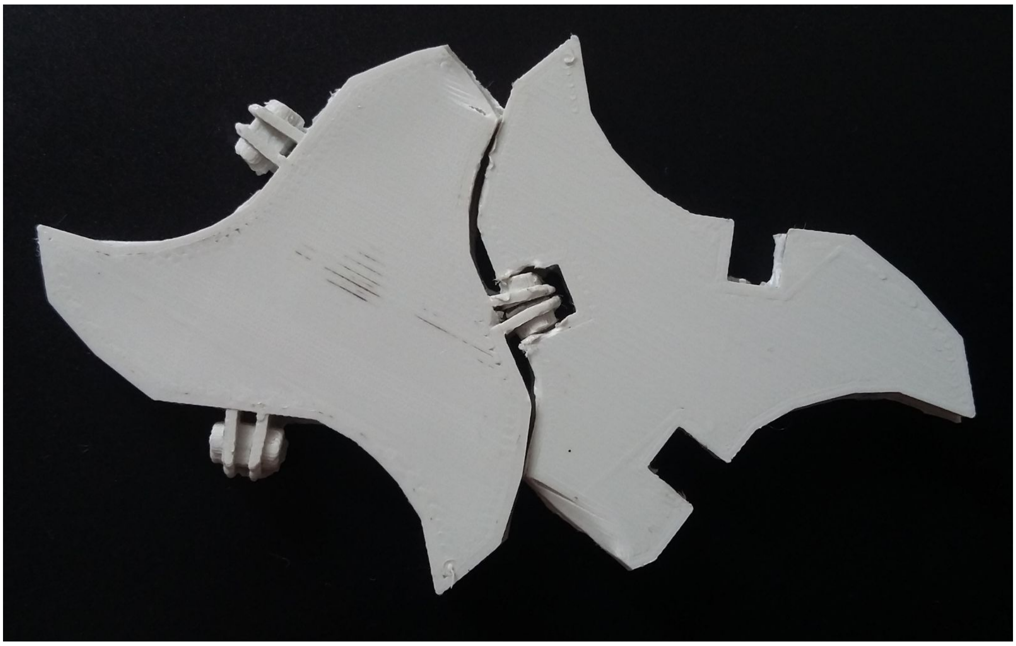


Figure 17, poorly aligned, but otherwise almost functional hinges

Step 7

Starting point
A 3D model that doesn't align properly.

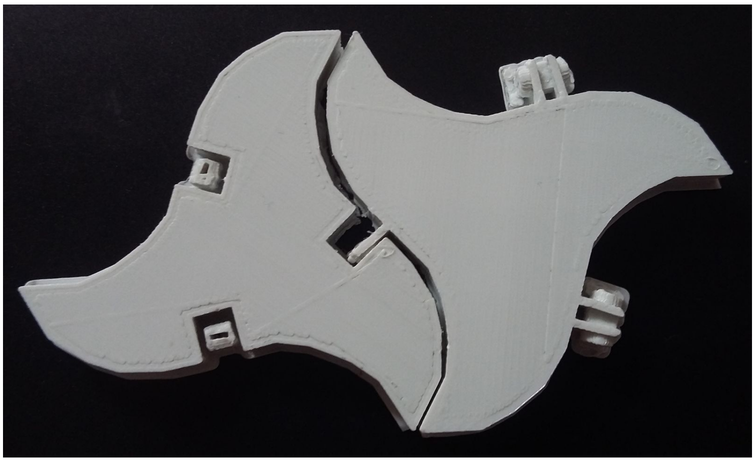
Goal/question
To adjust the model so that the edges and the mechanism align properly, and to figure out how to remove the extra material that the printer produces.

Experiment
The model was adjusted and then printed again. This time, no support structures were generated in Cura, and the brim that attaches the model to the plate of the 3D printer was made as small as possible.

Observation
The pins turned out to print properly without support structures, which saves some overall printing time. The extra material is still there. In removing it, one pin broke off, but this still allowed for testing if the mechanism works. The pin fits in the hole well. As with the cardboard test earlier, the thickness of the pieces gets in the way of the movement.

Conclusion
The extra material was not printed as consequence of the support structures that Cura generates, so more experimenting with settings is needed there. For the rest the mechanism seems to work as intended. The triangle needs to be rounded more to allow for better movement.

Pictures



Left: Figure 18, properly aligned and well fitting hinges. Right: Figure 19, movement along the axis is possible

Step 8

Starting point
A model with a mechanism that aligns properly, but is obstructed by its own edges and prints with material that isn't in the model.

Goal/question
To round the edges of the model and tweak the Cura settings more

Experiment
The top and bottom plane of the models were made smaller to create a rounded edge. The angle at which the sides stand is not too sharp so that no support structures are necessary. The models were printed without any brim

Observation
The extra material is still there. Removing it to test the mechanism was troublesome, and several out bits broke off entirely. The rounded edge allows for smoother movement, however, it also leaves holes in the outside of the in pieces.

Conclusion
The rounded edges work mostly as intended. They need to be tweaked a bit so that no holes in the side are created during printing. Some way to remove the extra material still needs to be found.

Pictures

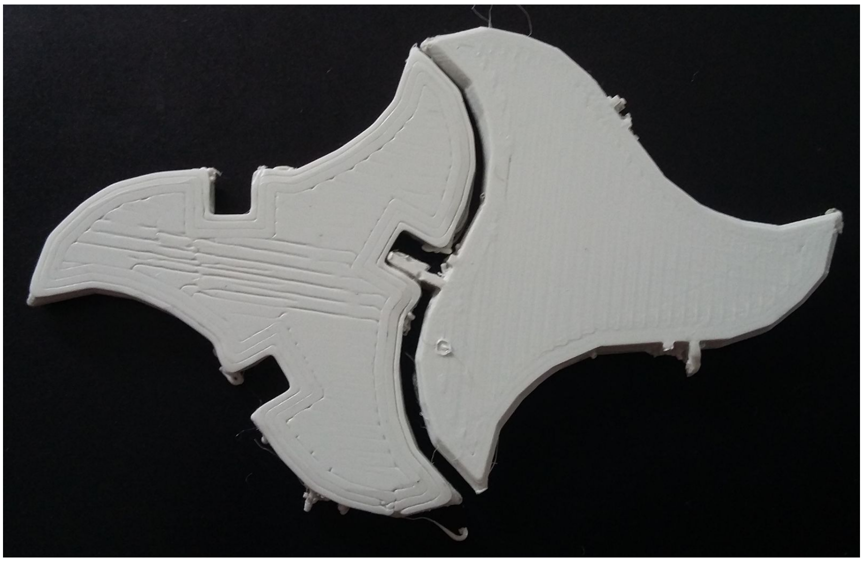


Figure 20, print with rounded edges

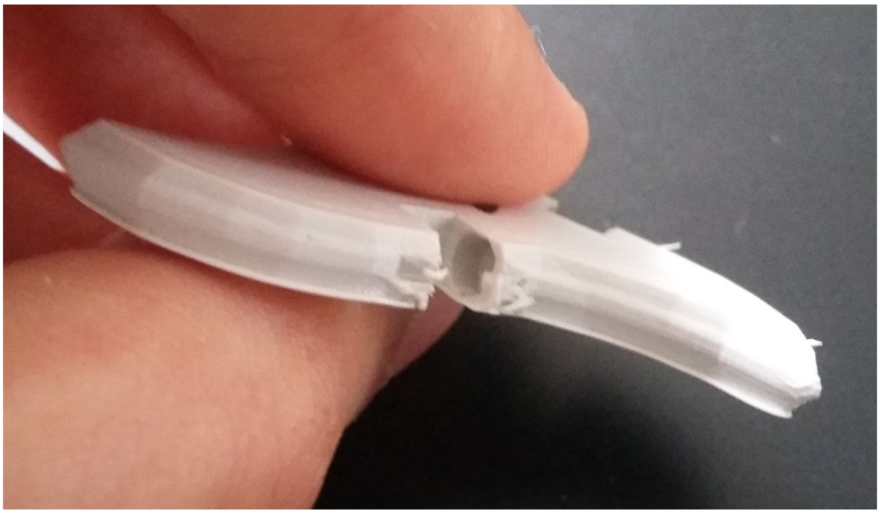


Figure 21, holes in the edges of the in print

Step 9

Starting point
A model with rounded edges and a connection mechanism that works, but which still prints with extra material that is not present in the model.

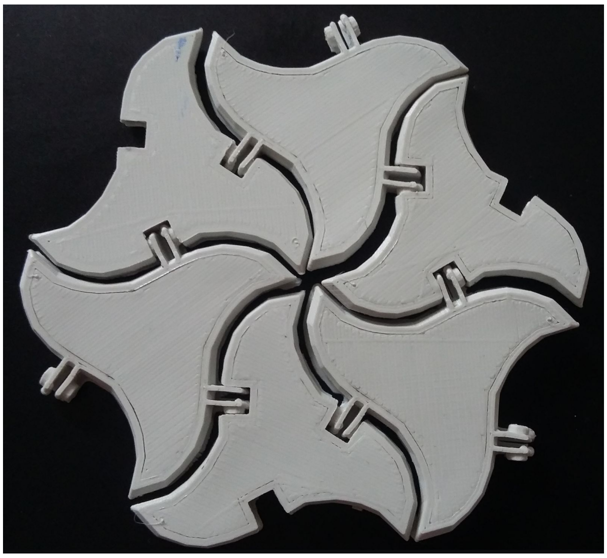
Goal/question
How can the printer be stopped from printing material not present in the model that obstructs the connection mechanism.

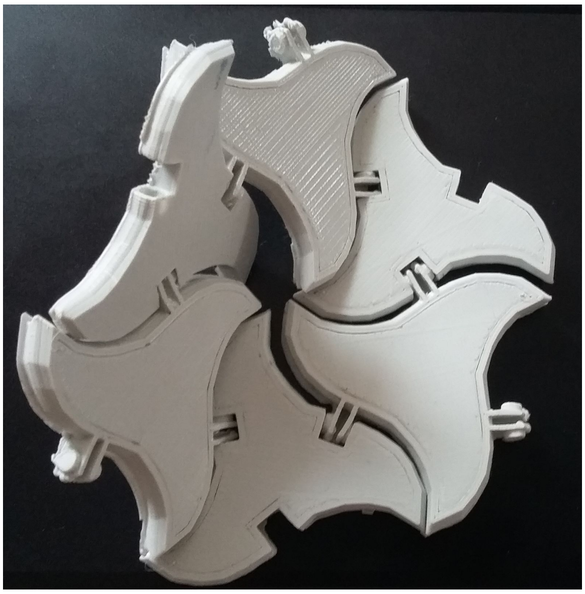
Experiment
The model was double-checked. All loose edges that Cura might misread were connected to the rest of the model. The holes in the in triangles were moved further inwards, away from the edge.

Observation
The model now prints entirely as intended. The extra material and holes in the side are both gone. The pieces click together properly too. Flexibility is limited due to the positioning and alignment of the hinges.

Conclusion
The hinges need to be positioned differently in order to achieve the desired flexibility.

Pictures





Left: Figure 22, the pieces click together properly. Right: Figure 23, movement is limited due to the placement of the hinges.

Step 10

Starting point
A model with fully functional but not ideally positioned hinges

Goal/question
To reposition the hinges in such a way that mobility is not limited

Experiment
The mechanism was moved to the points of the triangle. The positioning was made such that, when drawing a line between the hinges, the direction in which they bend is perpendicular to said line. At this point, both Ultimaker 2 and Ultimaker 2+ printers were used in order to speed up the process of bulk printing.

Observation
The structure as a whole now bends properly along every axis. Because of the point of attachment, it does have rather large holes in it when bent.

The printers showed significant differences in the accuracy of the prints: the Ultimaker 2+ created smooth prints, but the Ultimaker 2 would leave threads of material between the points of the out piece. These break off fairly easily and do not significantly inhibit the functionality of the hinges, however there is a slight chance of the out bits breaking off when trying to remove these. They also make the hinges move with more resistance.

Conclusion
When positioning the hinges on the triangle, it is important to note their relative position. The position of the hinge on the triangle likely affects the way in which the fabric as a whole moves and leaves holes. More repositioning of the hinges to achieve different effects should be possible. However, at this point in the process time restraints are becoming dire, and in order to be certain that at least the pessimistic goal specified earlier is reached, the choice is made to continue printing more of this model rather than experiment with the placement of the hinge.

Pictures

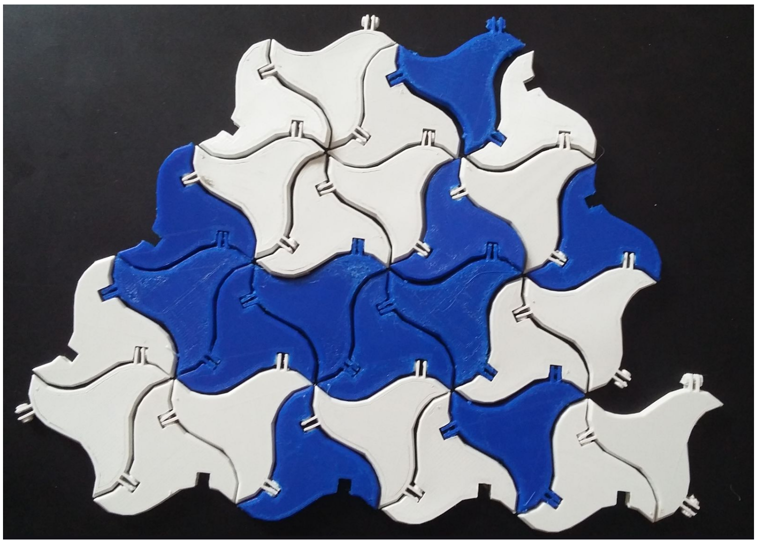


Figure 24, the structure when lying flat

Figure 25, the structure when bent. Movement along each axis works as intended.

Evaluation

The product is evaluated in three ways. First, a previously interviewed expert is asked to assess the product. Second, a number of non-experts are asked to evaluate the product with the aid of a questionnaire. This is because the product is intended for people with many levels of knowledge (or lack thereof) in both 3D printing and fashion design - only asking an expert will not give an accurate image of the desirability of the product. Finally, a personal assessment reflecting on the ways in which the design could be improved, and steps which would have been taken had the means to do so been available.

Expert assessment

The expert asked for this is Hellen van Rees, since it is possible to physically show her the product.

Van Rees was enthusiastic about the product, but also thought the current product did not yet meet the requirements set at the start. Most of her suggestions on meeting them consisted of improvements on what is already there: make the pieces rounder, the connections more sturdy, and the movements smoother. She also suggested experimenting with different kinds of filaments may be in order, as (smooth) plastic on skin often feels sticky and uncomfortable.

Besides these suggestions for improvement, Van Rees also noted that there may be different applications for a 3D printed textile besides clothing. An example she gave was lampshades: the space between pieces as well as the possibility of leaving pieces out of the pattern could create some interesting lighting effects.

Another expert, contacted specifically for this evaluation, is Judith Weda. She is a former Creative Technology student who has experience making wearable technology, as well as with general fashion design. Weda's commentary was similar to that of Van Rees in that while the product looked promising, it needed to be smoother and sturdier before really working as a fabric. Her main suggestion was to make the pieces thinner and thus lighter and less bulky. She also mentioned that jewelry might be a potential use, and was so enthusiastic about this prospect that she had effectively already clicked pieces together into a bracelet when mentioning it.

Public assessment

For the public assessment, several people with varying levels of knowledge in the fields of 3D printing and/or fashion design were shown the product, given a short explanation of what it is, and given a short questionnaire to answer. The full questionnaire can be found in appendix C. A scale of 1 to 6 was chosen for the questions to avoid neutral or indifferent answers and ensure that some form of preference would show in the results. When filling in the questionnaire several evaluation subjects required clarification that the first set of questions referred to the product as it is now, rather than its concept and potential future state. This may have affected the answers as there may have been some people who required this clarification but did not ask for it.

When handed the product, many evaluation subjects had positive verbal reactions. They appeared impressed with the concept of making textiles using a 3D printer and with the fact that a flexible structure had been created at all.

As shown in figure26, the actual ratings of the flexibility and comfort of the product are not quite as positive, receiving average or below average scores from most subjects. Interest in wearing clothing made with the product is also on the low side, likely because of these low ratings on comfort and flexibility. Despite this, the interest in working with the product is more spread out, with several people stating that they would almost certainly end up experimenting with it if given the opportunity.

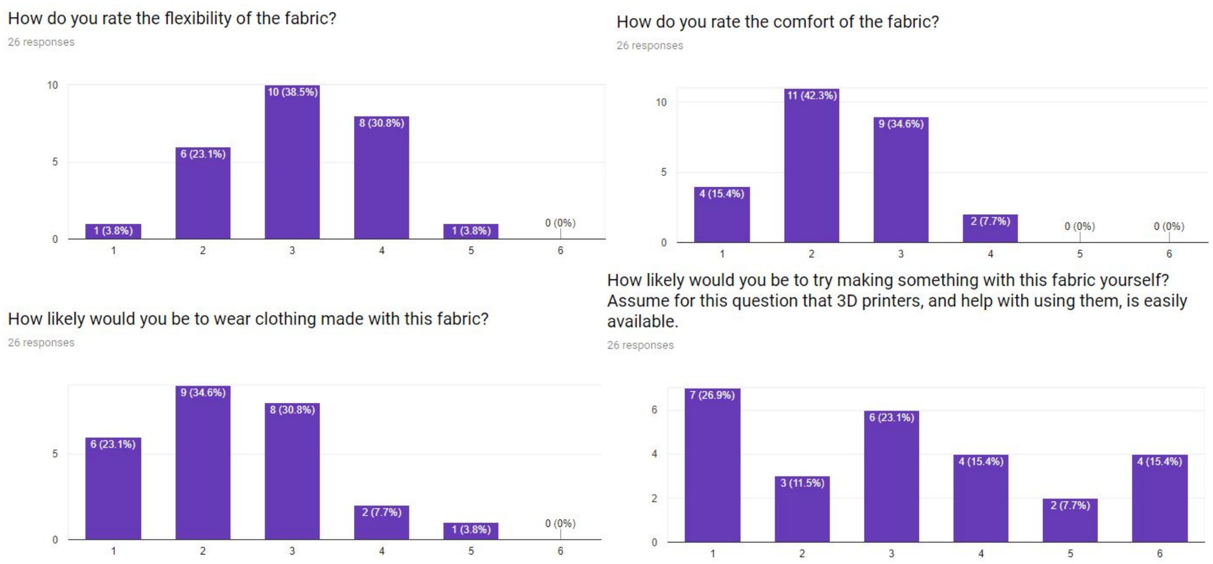


Figure 26, ratings of the current product

Suggestions for improvement were similar across subjects. The most common response was that the pieces should be smaller in order to increase the overall flexibility, followed by suggestions to improve the smoothness of the connections between pieces and to find some way to counter the hard, uncomfortable feel of plastic.

Out of 26 responses, the following suggestions were given more than once

- Smaller pieces: 13 times
- Smoother/more flexible hinges: 7 times
- Softer feel to the material: 7 times
- Thinner pieces: 4 times
- Rounder edges: 4 times
- Sturdier connections: 4 times

When considering these future improvements, subjects report being more willing to wear clothing made with 3D printed fabric. Interest in working with this improved 3D printed fabric also appears slightly higher, although it is still spread out. This indicates that, although the current product does not adhere to all the set criteria, people seem to have faith that it will do so in the future and have an interest in using it once it does.

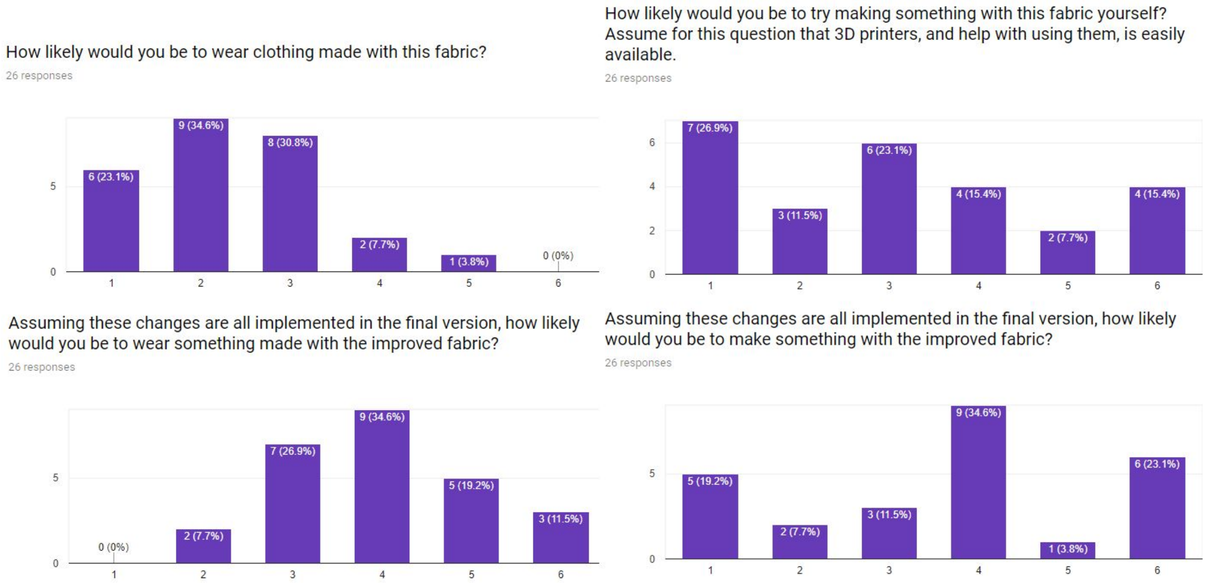


Figure 27, reported likeliness to wear/work with the fabric as it is now (top) vs an improved version (bottom)

Personal assessment

Much of the feedback obtained during the evaluation process consisted of things I had considered as well. The things I would like to pay attention to in particular in further development are as follows:

The hinges are still far from perfect, and after the product was passed around several people and got bent a lot, they would tend to disconnect. This compromises the durability of the fabric as a whole and definitely needs to be resolved somehow in later versions. The problem appears to lie with the out pieces getting bent out of shape, so tweaking these further should bring improvements in this area.

When it comes to making pieces of a smaller size, it might be worth it to consider different ways of connecting them altogether, since there will be a limit to how much smaller the current hinges can be made before they no longer work or the printer can no longer print them correctly. Something like a ball joint might be possible and would also increase overall flexibility, although whether the Ultimaker is able to print workable spheres at a small size remains to be seen.

I would also like to experiment more with the placement of the connections The current placement at the points of the triangles allowed for easy alignment of the movement axis in the face of time restraints, but it also leaves large holes in the pattern when bent. These holes will likely be reduced if the point of connection is somehow moved back to the middle of the piece.

Experimentation with different filaments is encouraged for anyone choosing to explore this field. The hardness and texture of common filaments is one of the largest obstacles standing in the way of comfortable 3D printed textiles right now. As mentioned earlier in this report many different novelty filaments do exist however, so it is likely that a filament that would improve the feeling of the pieces against the skin already exists. Something that has a fuzzy texture when printed rather than the smooth surface of plastic is likely to give better results.

Printing pieces of different sizes can create more interesting visual effects. Fabric on parts of the body such as the torso or the upper arm does not need to be particularly flexible, so pieces can be relatively large there. Around the joints the flexibility of smaller pieces would be far more important. Shifting the size of pieces depending on the need for it would make for interesting patterns if the shapes can somehow be made to still fit into each other at different scales.

Developments in the field of 3D printing itself will also aid the development of this particular 3D printing project. The Ultimaker 2 and Ultimaker 2+ showed stark differences in print quality, and even more precise printing will undoubtedly become possible in the future. Printing also still takes a lot of time, which improved printers will hopefully remedy as well. Perhaps SLS printers will become easily commercially available too within the nearby future. Even if further development of the project using the current technologies hits a dead end, it will be possible to try again in a few years using new and improved technologies.

Conclusion

The overarching goal of this project was to discover methods to create an item of clothing using a commercially available 3D printer. The optimistic goal of creating a full item of clothing turned out to be too ambitious for the given time restraints. However, the pessimistic goal of creating a piece of fabric that at the least shows promise of becoming a useable fabric has been achieved.

What has been created in the span of this project is a flexible structure made entirely with a commercially available 3D printer. It is still a prototype and does not yet adhere to the criteria of fabric set at the start of the process, but experts and laypersons alike believe that it can do so in the future if developed further, and have an interest in working with the fabric once it has in fact been developed further. There are many possible ways in which the basis set here can be expanded upon in further research.

Thus, the research question can be answered as follows: one possibility of creating clothing using a commercially available 3D printer is by printing numerous small pieces that, when clicked together, form a flexible structure that can be shaped into whatever garment is desired. It is very much possible that, within the nearby future, you *would* download a T-shirt.

References

Armstrong, K. (2016, September 15). 3D printed dress debuts at New York Fashion Week [Web log post]. Retrieved April 19, 2017, from https://3dprintingindustry.com/news/3d-printed-dress-debuts-new-york-fashion-week-95736/

Beecroft, M. (2016, 07). 3D printing of weft knitted textile based structures by selective laser sintering of nylon powder. *IOP Conference Series: Materials Science and Engineering, 137*, 012017. doi:10.1088/1757-899x/137/1/012017

Continuum. (2014). Myth Shoes. Retrieved 19 April, 2017, from http://www.continuumfashion.com/3D-printed-shoes-2014.php

Duann. (2014, July 03). *Revealing Dita Von Teese in a Fully Articulated 3D Printed Gown*. Retrieved April 17, 2017, from https://www.shapeways.com/blog/archives/1952-revealing-dita-von-teese-in-a-fully-articulated-3D-printed-gown.html

Grimmelsmann, N., Meissner, H., & Ehrmann, A. (2016, 07). 3D printed auxetic forms on knitted fabrics for adjustable permeability and mechanical properties. *IOP Conference Series: Materials Science and Engineering, 137*, 012011. doi:10.1088/1757-899x/137/1/012011

Hudson, S. E. (2014). Printing teddy bears. *Proceedings of the 32nd Annual ACM Conference on Human Factors in Computing Systems - CHI '14*. doi:10.1145/2556288.2557338

Kniterate. (2017). Kniterate: The Digital Knitting Machine. Retrieved 19 June, 2017, from https://www.kickstarter.com/projects/kniterate/kniterate-the-digital-knitting-machine

Korger, M., Bergschneider, J., Lutz, M., Mahltig, B., Finsterbusch, K., & Rabe, M. (2016, 07). Possible Applications of 3D Printing Technology on Textile Substrates. *IOP Conference Series: Materials Science and Engineering, 141*, 012011. doi:10.1088/1757-899x/141/1/012011

Melnikova, R., Ehrmann, A., & Finsterbusch, K. (2014, 08). 3D printing of textile-based structures by Fused Deposition Modelling (FDM) with different polymer materials. *IOP Conference Series: Materials Science and Engineering, 62*, 012018. doi:10.1088/1757-899x/62/1/012018

Michalska, A., Thomasson, E. (2017, April 7). *Adidas to mass-produce 3D-printed shoe with Silicon Valley start-up*. Retrieved April 17, 2017, from http://www.reuters.com/article/us-adidas-manufacturing-idUSKBN1790F6

Nervous Systems. (2014). *Kinematics Dress*. Retrieved from http://n-e-r-v-o-u-s.com/projects/sets/kinematics-dress/

Nervous Systems. (2016). *Kinematic Petals Dress*. Retrieved from http://n-e-r-v-o-u-s.com/projects/tags/3dprint/albums/kinematic-petals-dress/

Nottingham Trent University. (2016, June 16). *Bespoke 3D Printed Lingerie Does Away With Traditional Elastic*. Retrieved from http://www4.ntu.ac.uk/apps/news/187234-15/Bespoke_3D_printed_lingerie_does_away_with_traditional_elastic.aspx

Pei, E., Shen, J., & Watling, J. (2015, 08). Direct 3D printing of polymers onto textiles: Experimental studies and applications. *Rapid Prototyping Journal, 21*(5), 556-571. doi:10.1108/rpj-09-2014-0126

Peng, H., Mankoff, J., Hudson, S. E., & Mccann, J. (2015). A Layered Fabric 3D Printer for Soft Interactive Objects. *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*. doi:10.1145/2702123.2702327

Peleg, D (2014) *How I 3D-Printed a 5-Piece Fashion Collection at Home*. Regrieved April 18, 2017, from http://danitpeleg.com/3d-printing-fashion-process/

Sabantina, L., Kinzel, F., Ehrmann, A., & Finsterbusch, K. (2015, 07). Combining 3D printed forms with textile structures - mechanical and geometrical properties of multi-material systems. *IOP Conference Series: Materials Science and Engineering, 87*, 012005. doi:10.1088/1757-899x/87/1/012005

Sanatgar, R. H., Campagne, C., & Nierstrasz, V. (2017, 05). Investigation of the adhesion properties of direct 3D printing of polymers and nanocomposites on textiles: Effect of FDM printing process parameters. *Applied Surface Science, 403*, 551-563. doi:10.1016/j.apsusc.2017.01.112

Sensoree. (2017, February 21). *3D Print Fabric - Goosebump Fractal.* Retrieved April 17, 2017, from http://www.instructables.com/id/3D-Print-Goosebump-Fractal-Fabric/

Vanderploeg, A., Lee, S., & Mamp, M. (2016, 08). The application of 3D printing technology in the fashion industry. *International Journal of Fashion Design, Technology and Education,* 1-10. doi:10.1080/17543266.2016.1223355

White, J., Foley, M., & Rowley, A. (2015, 09). A Novel Approach to 3D-Printed Fabrics and Garments. *3D Printing and Additive Manufacturing, 2*(3), 145-149. doi:10.1089/3Dp.2015.0019

Appendixes

Appendix A

E-mail interview with Kirstin Neidlinger, 28 february 2017

What are some things that make 3D printing appealing to you as a technique?

3D printing offers enhanced detail and accuracy and greater speed than hand craft.

What is your design approach when working with 3D printing (e.g. how do you decide on what shapes/colours/etc to use)?

I endeavor to make 3D printing more wearable, flexible, and fun! I try to mix the prints with flexible substrates. The NEUROTiQ design has a knitted fiber optic base that we embedded the 3D prints in.

Inspired by the human body that requires connective tissue betweens the bones, SENSOREE has created this fractal fabric with joint material between the 3D prints. In this way, the fabric mimics our articulations, movements, and expressions.

tutorial: https://www.instructables.com/id/3D-Print-Goosebump-Fractal-Fabric/

Is this different from working with other techniques? If so, how?

3D printing is another material. Different filaments offer hard or flexible functionality. As with any material it is best to find the limits and then how they can intermingle with other components like electronics or textiles. There are always brilliant mistakes and invention.

What difficulties do you most often come across when working with 3D printing?

The main difficulty is sizing correctly. One mm can throw off the design and render it useless. Then, resizing to reprint. The waste this creates is a problem. I personally try to use PLA as it is bioplastic and will decompose eventually.

What do you think is the future of 3D printing? What developments would you like to see (regardless of current feasibility)?

I love the MADE IN SPACE project that allows the space station to 3D print tools that are rendered on earth. There are also interesting developments in architecture with printing materials like clay. For space travel, 3D printing robots promise settlements to be built on Mars before settlers arrive. I think this is very exciting for survival in new harsh environments.

Appendix B

Summary of interview with Hellen van Rees, 24 May 2017

Guiding questions of the interview are in bold. These were the questions the interview was intended to answer.

What are the most important things you consider when designing a new fabric?
-The flexibility
-The texture
-The comfort
What are some of the things that make 3D printing appealing to you as a technique?
-The freedom in what shapes are possible to make
-The possibility to combine with textiles to create different kinds of textures
Your website mentions that you value human handiwork highly. How would you reconcile this with 3D printed fashion?
-You don't at this point, basically. Maybe some kind of algorithm that creates random transformations, but that is outside my field of expertise.
Sustainability plays a big role in your designs. What are some of the ways in which you try to make your designs sustainable?
-Using leftover materials from mass produced items. Mass production requires large amounts of spools of thread to weave fabric, and when only one is left it can't be used for machine weaving anymore. Usually this still large amount of thread is then thrown out.
-Making patterns that leave as little leftover waste as possible, such as skirts cut out of a square.

Other insights
-The biggest hurdle in terms of comfort is the material qualities of plastic. Hardness aside, if it were possible to make plastic less sticky and sweaty it would likely improve overall comfort a lot.
-When it comes to finding ways to connect the pieces, it might be worth to look at different kinds of children's toys.
-There is a kickstarter for a knitting machine called Kniterate, which intends to make it easier for people to design their own fashion similar to this project. Their work might be interesting to look at
-If your model ends op working well, you could use the textile for far more than just clothing. It could have a nice effect as a lampshade, and you could create all kinds of interesting effects by purposely leaving holes

Appendix C

Questionnaire for evaluation

- What is your age?
    - Free answer
- What is your gender?
    - Male
    - Female
    - Other
- Have you worked with 3D printing before in any way?
    - Yes
    - No
- Have you made or designed clothing before in any way?
    - Yes
    - No
- How do you rate the flexibility of the fabric?
    - 1-2-3-4-5-6
- How do you rate the comfort of the fabric?
    - 1-2-3-4-5-6
- How likely would you be to wear something made with this fabric?
    - 1-2-3-4-5-6
- How likely would you be to try making something with this fabric yourself? Assume for this question that 3D printers, and help with using them, is easily available.
    - 1-2-3-4-5-6
- The fabric as shown is still a prototype. What are some suggestions you may have for improving the fabric?
    - Free answer
- Assuming these changes are all implemented for the final version, how likely would you be to wear something made with the improved version of the fabric?
    - 1-2-3-4-5-6
- Assuming these changes are all implemented for the final version, how likely would you be to make something with the improved version of the fabric?
    - 1-2-3-4-5-6