Possibilities of Fabric Embeds in 3D Printing

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Abstract

3D printers are widely known for easy-to-use prototype crafting, yet come with limitations such as fixed input materials and long printing times. One approach to overcome some limitations is the use of fabric as a material, extending 3D printing overall. This paper presents an introduction of 3D printing and fabrics, their combination and resulting advantages. Furthermore, an extended review, comparison and discussion of related work with the focus on new research possibilities, different printing methods using fabric, as well as their results will be shown.

Introduction

3D printers gained a lot of popularity in recent years. Not only can you print whatever your heart desires in a very detailed way, they are also very accessible, affordable and user-friendly. In addition of opening new research possibilities, 3D printers create new opportunities of craftsmanship as well.

Nonetheless, they come with a lot of limitations. For instance, the materials needed for most 3D printers are generally limited to plastic, metal and resin. Next to the materials, printers can have different printing methods depending on the material, such as Direct Metal Laser Sintering (DMLS) [12]. In other words, not every 3D printer can use every material and printing technique, limiting printing options.

Adjacent to printing techniques, 3D printers need a lot of time to create a prototype. As a way to extend 3D printers and to overcome some limitations, fabrics are a great option. Apart from being very known and widely used, fabrics have very desireable qualities, in particular being deformable yet durable and the possibility to support interactivity, namely sensors. Thanks to their structure, they enable rapid rather than slow prototype crafting by using the material as-is and provide new research possibilities. In this paper we will present and discuss the combination of 3D printers and fabrics. Furthermore, basic and extended printing techniques using fabric will be introduced, as well as different reasearch topics that opened up by combining 3D printing with fabrics.

Preliminaries

Before starting to talk about the main aspects of this paper, we will present the basic functionality of 3D printing and how it can be used to introduce different printing techniques using different materials, in this case fabrics.

Functionality of 3D Printing

Many 3D printers use plastic as a means to create prototypes, printing one layer at a time, one layer on another. This method is also known as fused despositional modeling (FDM) [1]. Traditionally, there are two main parts to consider to successfully create a 3D prototype using a 3D printer. One is the use of software, the other is the 3D printer itself.

The software is needed to control the 3D printer and to process a computer-aided design (CAD), a 3D image, as seen in Figure 1. The first step of 3D printing is to process the 3D image using corresponding software. During the process, the 3D image will be sliced horizontally to prepare for the FDM method and a plan to control the hardware of the 3D printer is created.

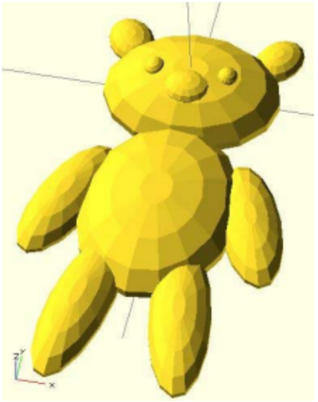

Figure 1: An image of a 3D CAD [6].

The 3D printer generally consists of a heating element, a platform to print on, a head to deposit material and motors to control the X-, Y- and Z-axis to control head movement. Initially, the raw material of the 3D printer is led through the heating platform to melt the material to a specific degree. It is then placed on the platform by the head in the shape of the first layer of our CAD by moving along the X- and Y-axis. Once the first layer is done, the head moves up on the Z-axis so that it can continue printing on top of the previous layer. Through the semi-molten state, the plastic layers merge with each other and thus create the final prototype. If one wants to extend 3D printers by using a different material, hardware or printing method, then the printer itself and the software may need adjustment. For instance, a more heat-resistant material can make the heating platform obsolete, or the material cools down too fast and the software processing settings must be considered. Different approaches and solutions to this problem will be presented in the section "Extending 3D Printers".

3D Printers and Fabric

In this chapter we will discuss the motvation behind using 3D printers and introduce fabrics itself and as a material for 3D printing. Furthermore, different approaches on dealing with textiles in 3D printing, how to extend 3D printers, research results as well as new possibilities will be shown.

3D Printing

Overproduction and a throw-away society are dividing this world. Main aspects such as sustainability and decentralization in terms of equality are becoming more and more important for the future of preserving this world. 3D printing, as a steadily evolving technology, has expectant glances towards the future. This technology opens up new ways to create custom, sustainable, decentralized objects for individual needs.

3D printing and related technologies can focus on several areas, such as reducing waste, reusing materials, providing local and sustainable materials, manufacturing customized products, and localizing production.

The growth of the economy, population, technological innovation, and standard of living are leading to a natural resource depletion as humans continually extract natural resources. Therefore, we must strive for thoughtful use of materials and more effective production [7].

Benefits of 3D printing

The additive manufacturing process used in 3D printing reduces the material required by the exact amount needed to complete a product. In addition, 3D printing offers the ability to reduce or omit the filling of a product, allowing the same result to be achieved using less materials.

Another benefit of working with 3D printers is the ability to recycle materials. Waste is often generated from failed printing, prototyping, and support structures. Products with a short-term life span also benefit from this procedure.

With 3D printers you can create many different and complex prototypes with just one machine. The customizations that a product may need are possible at almost no additional cost and little effort thanks to supported software. Therefore, 3D printing enables a wide range of complex printing processes without the need of long processing times.

In general, 3D printers enable an alternative form of production that can eliminate dependence on the global market by creating prototypes locally, and promote creativity and innovation. You can create precise functional rigid objects with custom geometry, but there are limitations underneath [7].

Limits of 3D printing

The most common used materials for personal 3D printing are two types of thermoplastics: polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). These materials have the disadvantage that they cannot be used in environments where high temperatures are a concern, such as kitchen appliances or electrical equipment. Properties such as durability and stability are also limiting factors, depending on the application. Above all, however, there is a lack of properties, such as formability, stretchability and flexibility, which can be improved by embedding fabrics in 3D printing.

Another limiting factor, which arises because of the material, is the printing speed. The material has to be semi-melted, printed on another layer, and cool. This process is repeated until the prototype is done. For example, it takes about eight hours to produce a standard cube of fifty millimeters. This is indeed a slow pace, but it is necessary for good results when printing with thermoplastics [7].

Fabric

Fabrics have been used as a material for a wide variety of applications by humans for millenia. The main advantages of fabric stem from its ability to regain shape after it was deformed. It can be folded, stretched, compressed and twisted without losing its characteristics [11]. Its softness and being comfortable makes it a suitable material for clothing or to be ”held close” [6].

Fabrics consist of interlocked fibers, with a variety of many different types of fabric existing, depending on the fibers used and the method applied to interlock them. Fibers can be made of naturally occuring materials like cellulose, cotton, wool or silk, as well as a variety of manufactured materials like glass, carbon or ceramics [2]. Fibers made from purely synthetic materials are also possible, as we will see later when discussing electrospinning as a means to create fabrics from PLA. As such, one can see that fibers are very affordable and easily aquireable. While the listed materials are only examples, they show that the source material from which the fabric will be made of can differ significantly considering its origin and properties.

The method used to interlock fibers also greatly impacts the properties of the resulting fabric. Common methods used in the production of textiles are knitting, weaving and felting. These techniques in combination with the chosen fiber material can influence all traits of the resulting fabric, like weight, stiffness, softness, strength or resistance to strain, electrical conductivity, thermal insulation [3] and water permeability. Which of these traits matter, and thus which fabric is the best suited, depends on the application in which it will be used.

Working with fabric poses challenges to manufacturing processes: Unlike stiff materials, undesirable deformations like sagging may occur. Sagging can be prevented by applying tension to the fabric [11]. Another challenge is rotating the fabric, which requires a different approach than rotating a stiff object, in which twisting may not occur. Also, when working with fabrics, one usually wants to attach a variety of things to the fabric, like other fabrics, or in the scope of this paper, plastic filaments. Appropriate methods to ensure the attached materials stay bound to the fabric are required and depend heavily on the material at hand.

Figure 2: A teddy bear printed with Hudson’s felting printer [6].

Extending 3D Printers

In order to benefit from the properties of fabrics in 3D printing, several research teams have proposed methods to embed fabrics as a material into the printing process, extending 3D printing overall.

In 2014, Hudson published his paper about a 3D felting printer [6]. Felt itself is a fabric that is gained through compressing sheets of fibers. Hudson’s 3D printer is very alike a normal 3D printer, using horizontal slices and combining them layer-by-layer to reach the desired final geometry, for example a teddy bear as seen in Figure 2. However, rather than semi-melting the material, in this case the layers are bonded together by needle felting. A yarn is placed in a path such that it fills the entire slice of the current layer. While placing this yarn, a felting needle is repeatedly pierced through it, in order to drag individual fibers

of the yarn down into the lower layers and entangle them there. This bonds the two layers together and creates the typical look and feel of felt. This method can support overhangs of up to 55°, even though the print quality reduces at such steep angles. A custom felting print head was engineered to accomplish this task, the remaining hardware is similar to common 3D printers and the process is very similar to normal FDM printing, where plastic is placed in thin lines to form a layer. In fact, Hudson used an existing FDM printer and just swapped the print head for his custom one. He even used a standard slicing and path planning software for FDM printers, coupled with a custom post-processing software to drive the printer.
It is also possible to integrate electronical or mechanical components into the build process by creating pockets in the prints, in which the components can be inserted, so that they would not interfere with the felting needle.
To reduce the stiffness of the printed object, it is possible to leave small holes in some layers in which the surrounding layers can fold into. The author also tried two methods to increase the stiffness, first by using a less flexible material on some of the layers, and then by inserting a nylon mesh embedded within 3D printed plastics into the object.
The latter method proved to successfully improve the stiffness of the print and not interfere with the needle.

Pei et al. [8] used entry-level FDM printers and 3D CAD solids to determine if hard complex parts could be printed directly onto fabric without losing any benefits of either material. The goal of this study was to find a way to combine polymer with fabrics, so that limitations and possible applications can be found. For instance, fabric is a very breathable, deformable and comfortable material whereas polymer can strengthen the structure of any given soft object. The filaments consisted of either ABS, PLA, or nylon and were tested on 8 different fabrics, such as woven cotton to see if hard objects could be integrated with textiles.
Before starting to combine fabrics with solids, three areas had to be considered for effective deposition. The first one being the binding and adhesion of polymer and fabric, the second being not influencing the free movement of fabric on the printed parts and lastly, the resistance of deformation to withstand daily wear.
The fabric was put on the printing platform and held together by clips, the filament was then printed onto the fabric. During the study, printing factors were kept consistent to not alter results, namely temperature, speed, fill amount, layer height and print density. It is seen that PLA has overall good compatibility with fabrics displaying high quality print with good adhesion and flexural strength, while only having little warp and material distortion. Furthermore, woven cotton, woven polywool and knit soy have good compatibility with all three filaments.
Through this study, new possibilities arose. For instance, the combination of wearable electronics integrated in textiles with hard parts without loss of quality. This can be used for medical purposes like orthopaedic braces. Moreover, combining the findings of Peng et al. and Pei et al., one can wonder if a 3D printer can be made that combines both printing with fabric and plastic, to further increase reasearch- and practical possibilities.

In the same year as Pei et al., Peng et al. [9] used a different approach of extending 3D printing by using fabrics. They too used a layered approach, but almost completely overhauled the hardware. Next to the standard construction of a 3D printer, mirrors, a laser head and a laser tube with a heating disc, a bonding platform, and a cutting platform with a vacuum table are built in. The main difference lies in the usage of two different platform, where one is used for cutting the fabric and one for bonding it, as well as support printing with two different fabrics. Due to the fact that they

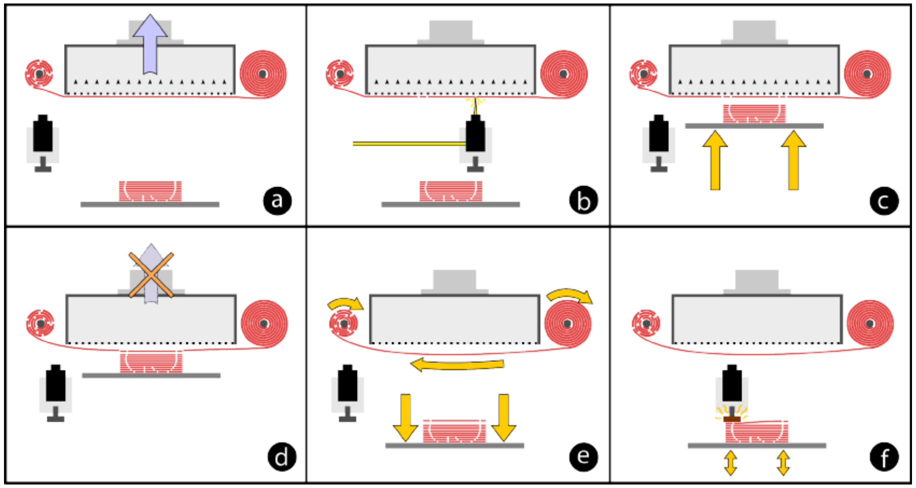

Figure 3: Schematical of the workflow of the printer presented in the paper of Peng et al. [9].

used a laser to cut the fabric they had to turn the cutting bed upside down, in order not to cut into the lower layers. The software and slicing however, is standard and unmodified.

Before printing, the fabric is prepared with a fusible adhesive and then fed to the printer, and the bonding platform is covered in a layer of fabric. Same as a FDM printer, the heating disc is heated as well before feeding the material to the printer. The first step of this printer is to turn on the upside-down vacuum table, thus creating suction in order to hold the fabric in place, so that the fabric is being held towards the cutting table (Figure 3a). Followed by cutting a 2D layer shape and a bounding box into the fabric (Figure 3b). The layer will remain connected to the bounding box via very thin sections of fabric. This increases the stability while printing and can easily be peeled away when printing is finished. After cutting is finished, the bonding platform with the previous layers will rise from the bottom of the printer to touch the newly cut fabric layer (Figure 3c). The vacuum is then turned off in order to release the cut fabric 3d), after which the bonding platform is lowered again, taking the new layer with it 3e). A heating disc will then be used to activate the adhesive glue and bond the new layer to the previous one 3f). This process is repeated for each layer, until the printing is finished. Since this printing method cuts bounding boxes into the fabric, the bounding boxes from each layer will still be present and the result will be a fabric cube. The extra fabric can be peeled off to reveal the final 3D fabric object.

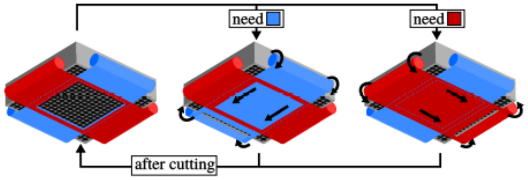

Figure 4: Printing with two materials [9].

Considering printing with two fabrics is supported by the printer, opportunities such as constructing interactive objects or 3D objects with additional variations were made possible. This is achieved by feeding two fabrics into the printer, where one fabric is being fed left-to-right and the second fabric front-to-back (Figure 4). Before the fabrics are printed, a bounding box in the form of a window will be cut into them and during the print, the material needed in the next layer will be advanced.

The goal of this study was to enable prototyping of interactive devices using off-the-shelf conductive fabric with as little intervention as possible. As presented in the paper, one possibility to achieve such feat is to use a non-conductive fabric together with a conductive one, using the dual-material printing method. For instance, wiring between electronic components inside the fabric are possible by connecting the conductive layers at specific points. To accomplish said connection, a non-conductive layer is placed between two conductive layers. However, this also came with problems such as the adhesive not being strong enough, or that the heating disc had to be placed further down to successfully connect the conductive with the non-conductive layer.

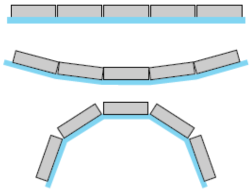

Figure 5: Bonding plastic strips to one side of the fabric prevents bending in one direction, thus creating selective stiffening [11].

Continuing with Rivera et al. [11], in 2017 they published a paper in which they used fabrics in 3D printed objects in order to benefit from fabrics' properties. In contrast to the papers presented by Hudson and Peng et al., they did not construct a new printer, which would be able to use fabrics as a printing material, but instead worked with a normal FDM printer that uses plastics as its printing material. They paused the printing process at certain points to manually insert pieces of fabric where they were needed. This allowed them to experiment with the properties one gets by combining a stiff material like plastic with a soft one like fabric. Selective stiffening (Figure 5) is achieved by printing plastic onto certain parts of the fabric and thus stiffening the fabric along certain areas, preventing it from bending or stretching in certain directions. Rivera et al. also managed to control the degree of bend angles by placing stiffeners very close to one another. The angled sides of those stiffeners determined how far the fabric could be bent. These two techniques were used to create a flexible watchband.

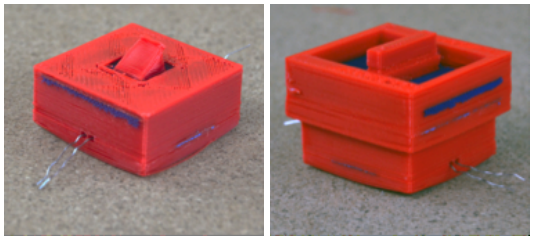

Figure 6: A displacement sensor and a retractable slider, which make use of fabric properties[11].

Selective adherence is the concept of allowing the plastic to only bond to selected parts of the fabric. In the paper of Rivera et al., it was achieved by placing painter's tape over those parts of the fabric on which plastic should be placed, but not adhere to it. This was used to create a mechanical slider, which automatically retracts with the help of stretchy fabric, as seen in Figure 6. While the ends of the fabric would be bond to the plastic encasing, the rest of it could stretch freely.

Building on the selective stiffening, Rivera et al. also experimented with manufacturing the stiffening plastic parts in such a way, that a certain simple mechanical action is achieved. In their example, a strip which is pulled will cause the lid of the box to curl up due to angles in the stiffened plastic parts.

Another idea from this paper is to replace layers, or faces of an object with fabric sheets, which are stiffened by a plastic shell in order to save printing time. Only the shell has to be printed onto the fabric, which can then be folded into the final object. This uses significantly less printing material and thus less time. This is an improvement from established printing techniques which often suffer from the problem of long printing times. Another possibility is to print snaps and clips onto the fabric, which have to be joined after the printing process, in order to bring the final print into its desired form.

Also, they explore the idea of printing objects which are larger than the printer itself, given the fact that the fabric can be moved between printing steps. The fabric could thus either be folded on the printing bed, or even moved off of it. Problems that arise largely stem from the fact that the fabric could end up in the way of the extruder nozzle. Also, moving the fabric manually might lead to inprecise placement. This can be tackled by printing an additional skirt layer as assistance to correctly position the fabric in the print bed, or by attaching a laser pointer to the print head to guide alignment.

The authors considered 3D printing as an option for fabric post-processing as well. In particular, they printed reinforcing grommets around holes cut into the fiber to protect the fabrics' raw edges from fraying.

While experimenting with these new ideas, the authors encountered some problems with the usage of fabric sheets as a basis to print on. The sheet is less stable than a solid foundation, meaning that it can shift around, stretch, sag or tilt. Rivera et al. tackled these problems by fixing the fabric in place with painter's tape.

Looking at a different research aspect of the play between 3D printing and fabrics, in 2020 Goudswaard et al. [4] presented a way to embed mechanical, tactile push buttons in textiles. Their idea was to boost human-computer interaction by creating on-body wearable user interfaces, using smart textiles as a very promising approach. The goal is to afford textile's physical landmarks, give rapid feedback to the user if pressed and having a reliable, steady electrical connection.

To do this, they used a combination of FDM-based 3D printing and digital embroidery. However, a frame system that unifies the workflow between embroidery and 3D printing

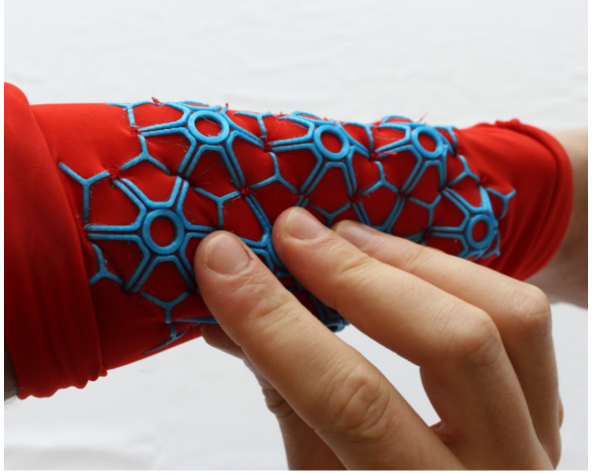

Figure 7: A sample sleeve of the FabriClick, where one button is being pressed [4].

was needed. As such, they invented a frame system consisting of 4 layers, with the first layer being the baseplate, the second being the 3D print frame, the third the embroidery frame and the fourth the inner support plate.
They found that a star-shaped design would achieve the desired behavior of a tactile button, since the central point and the several legs can control tension, as well as balance.
For instance, a small button size with 8 legs does not provide the needed flexibility. This design used spring tension to create what they called a 2.5D morphing shape, allowing them to embed structures in stretchable fabrics. FDM-based 3D printers were used to print the star-like shape onto pre-stretched fabric, with the tension of the legs being controlled by the thickness of the prints.
The overall process involved embroidering and 3D printing two separate layers and later reconnecting them with embroidery to create a combined e-textile (Figure 7).

Figure 8: The prototype of the electroloom as presented in the paper of White et al. [14].

Pursuing a different approach rather than applying FDM, White et al. present the use of an electroloom as a fundamentally different form of 3D printing in a 2015 paper [14].
In this approach, electrospinning is used to convert liquid solutions into non-woven, 3D-printed like fabrics with different properties and applications.
To use the electroloom, molds are placed inside the electroloom that define the size and shape of the desired fabric item. The molds are typically made of aluminium or other metals, but nonconductive materials that have been coated in conductive paint have been a success as well. In the electroloom, a fabric solution is sprayed into a high-voltage electric field within the machine, where a charged mold (Figure 8) is placed. Once the electrostatic forces overcome the surface tension of the solution, the fibers are drawn out of the liquid and attach themselves to the mold. When the layer of fabric on the mold is thick enough, the machine can be turned off and the final product can be taken off the mold.
The primary material used for prototyping in the electroloom

is polyester and cotton blend, which results in a material that feels like leather and is also water resistant. However, the main drawback is that since this process creates a non-woven fabric, it is lacking some of the most important features of other fabrics, such as flexibility and a reasonable amount of strength. Furthermore, it cannot be washed, since it breaks down when it is agitated. The solution the authors proposed for this problem is to just form the item back into a solution and create a new one from it. Nonetheless, silk fibers and acrylic fibers were to be used as possible future materials to overcome some problems. As such, electrolooms open new paths of research like blends with specific ratios of fabrics, or using a different fabric at a different layer.

Electrospinning was also used by Rivera et al. in their 2019 paper [10] to create tiny polymer fibers as a basis for fabric directly in the 3D printer. For this purpose, they developed a new 3D printer that combines melted electrospinning and rigid plastic printing using a single extruder. The print bed of the printer is used as the collector for the electrospun fibers. A challenge they tackled was the high voltage (5-50kV) used in electrospinning, which could disturb or damage other parts of the printer. For example, they found that a minimum distance of 1.5cm between the nozzle and the print bed had to be maintained to prevent arcing. Also, it was necessary to shutdown the high voltage components during normal printing and to discharge the print bed after each usage of the electrospinner. These procedures were automated by the authors using specially designed circuits and control software.
They experimented with different extrusion rates, temperature and infil density in order to create different fabrics. Faster extrusion rates create a more rigid material which resembles normal 3D printed PLA. A slower extrusion rate yields a more uniformly distributed and soft fabric. A similar result can be found for the temperature, where lower temperatures yielded more plastic-like results, while temperatures around 300℃ appeared to yield the smallest fibers and thus the softest fabrics. Increasing the temperature further led to inconsistent results.
To allow for the fabrication of soft sensors, the authors embedded conductive layers of copper sheet between the soft electrospun fabric layer. For this method, the printing process has to be paused to allow the manual insertion of the copper sheet. The result is a custom-shaped soft capacitive sensor. Another option to create soft sensors is to coat the electrospun fabric in piezoresistive paint. After the paint has dried, a change in electrical resistivity could be measured when manipulating the soft fabric.
Due to the electrospun fibers ability to absorb liquids, Rivera et al. were also able to create a liquid absorption sensor, by attaching electrodes at opposite ends of the fabric und measuring the voltage between them. They applied water droplets onto the fabric and the voltage between the two electrodes increased with every droplet, until the fabric was saturated. This method was used to create an actuated flower reminder that helps people remember to water their plants. They also created a foldable origami-style lamp, seen in Figure 9, that used the electrospun fabric surfaces to diffuse the light of the lamp. A piezoresistive sensor was printed to control the lamps' brightness, while a capacitive toggle switch was created to toggle the lamp on and off.

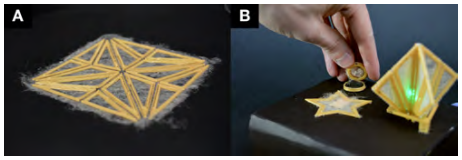

Figure 9: A 3D printed foldable origami lamp, using elctrospun fibers as a source material for fabric [10].

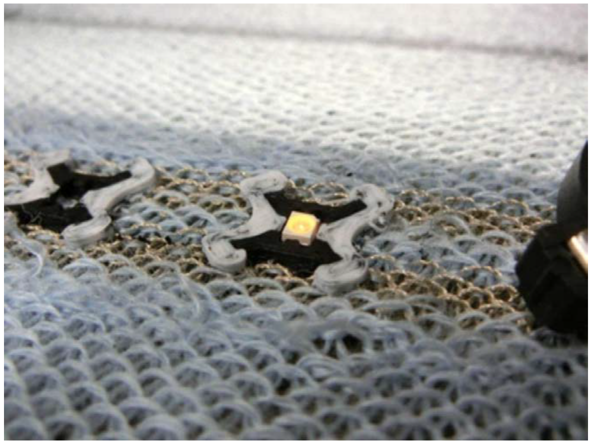

Figure 10: An SMD LED in a 3D printed holder cell, printed directly onto partially conductive fabric [5].

A paper by Sun et al., published in 2020 [13] explored the use of PLA material deformation to transform fabrics with carefully crafted PLA patterns printed onto them. The PLA is printed on top of the fabric to bond the two materials, and then the PLA is deformed in a controlled process using a garment steamer. A small basket could be created from this process, as well as a support structure for a face mask. The authors tested their methods using different fabrics and found out that not all fabrics are suited for this kind of process. Especially polyester is unsuited, as the PLA does not stick to the fabric because it is too smooth. The fabric that worked best for them was just described as ”sport fabric”.

In a 2016 paper by Grimmelsmann et al. [5], possibilities of 3D print connecting points between conductive fabric and electronic components were explored. The goal was to create a 3D printed holder cell for an SMD LED, which would connect to two seperate strips of conductive fabric, as shown in Figure 10.
For this purpose they experimented with a selection of different fabrics and filaments and compared the contact resistance of the connecting points between filament and fabric, as well as the resistance of different materials over various distances.
They showed that embedding the right conductive materials in between the layers of the filament can significantly reduce the resistance, in particular embedding Shieldex yielded the best results, while the embedding of stainless steel wire did not improve the result nearly as much.
Their product also showed to be washable in first tests, including the complete system and inset LEDs without batteries.

Discussion

As we have seen, fabric can be used and applied for a variety of purposes. In this chaper we will first discuss how good fabric really is for 3D printing and if future research can benefit from it. Afterwards, we will compare different approaches to 3D printing with fabrics and how to solve similar problems, discussing their respective advantages and disadvantages as well. Furthermore, we will take a closer look at embedding fabric in 3D printing, rather than printing with it and finish with 3D printing approaches that print on fabrics.

3D Printing with fabric as a material

We saw that fabrics are very desirable thanks to their properties, some being formability, stretchability and flexibility. Because of such desired properties, they have been used in a vast amount of applications, with one of them being a material for 3D printing.
Althought having these properties, as a matter-of-fact, fabric itself is not a suitable candidate for common practices of 3D printing. Existing printers that use methods like FDM

cannot utilize fabric as a fed material, heavily limiting the printing possibilities and requiring the modification of the printer. Peng et al. [9] approached this problem and presented a solution of using fabric as a 3D printing material in form of sheets. Even though printing layer-by-layer with sheets of fabric were made possible by this printer, the fabric itself became condensed or stiffed in areas that alter the final prototype form, which is an undesireable outcome.

To extend, we have seen 4 different approaches to use fabric directly as a material for 3D printing. Two of these facilitated pre-manufactured fabrics and two used electrospinning to create the fabric in the printer itself:

- Type A: Using pre-manufactured fabrics
  - Hudson 2014 [6]
  - Peng et al. 2015 [9]
- Type B: Using Electrospinning
  - White et al. 2015 [14]
  - Rivera et al. 2019 [10]

When comparing the two categories, differences become obvious quite early. The two proposed printing techniques that rely on pre-manufactured fabrics (type A for short) both share the characteristic that they mimic the workflow of a common 3D printer: The 3D model is sliced into layers and those layers are printed one after the other. They both produce a full 3D object that is made solely out of fabrics. The electrospinners (type B for short) on the other hand work vastly different. Fibers are just released into the air and find their way to the target via eletrical fields. This results in just a thin sheet of fabric being created at the desired location. Obviously, different advantages and drawbacks result from the proposed methods, which we will examine in detail.

A main concern in 3D printing always is printing time. We see a potential for high decrease in printing time in the method proposed by Peng et al. [9], since they use whole layers of pre-manufactured fabric sheets at once. Currently the method is still slow, but the authors claim it could be drastically improved by using a bigger heating element and more powerful motors to raise and lower the printing platform. Unfortunately we do not learn anything about the printing time of the felting printer by Hudson [6]. Electrospinning is inherently slow in itself, as stated by White [14]. They name the printing time as one of the biggest drawbacks of their method, but have also provided some insight in how it could be improved. For example, the time it takes to finish the process is apparently linearly dependent on the amount of nozzles used to release the fibers. We do not learn anything about the speed of the electrospinner in the publication of Rivera et al. [10], but we expect it to be even slower, since it uses only one nozzle. However, Rivera et al. only used this method to print small segments of fabric, while White et al. printed complete clothes.

Considering the precision of the proposed methods, one of them clearly sticks out as the winner. The electroloom of White et al. [14] will create an object that exactly mimics the shape of the mold used. The electrospinner on the 3D printer of Rivera et al. can only be used to print thin layers of fabric without a great amount of detail. After a thickness of 1.2mm is reached the electrostatic field will become too weak to further thicken the fabric. Also the nozzle cannot really precisely deposit fibers, since it has to maintain a certain distance to the print bed in order to prevent arcing caused by the high voltage. The level of detail in the two printers of type A is mainly determined by the thickness of the printed layers, which is 2mm (Peng et al.) and 2.25mm (Hudson) respectively. This is vastly inferior to common 3D printers using other materials, which usually operate between 0.2mm and 0.3mm and can thus replicate a lot more details of the original model.

Another aspect to consider is the strength of the printed objects. While the printers of type A work with pre-manufactured woven fabrics, which are known to withstand a good amount of pressure or stress, the electrospinners have shortcomings in this particular point. The textiles produced by the electroloom of White et al. [14] are not even washable. Unfortunately we do not learn anything about the strength of the electrospun fabrics in the 3D printer of Rivera et al. [10]

Embeddings in 3D prints

Embedding hard objects, electronics, and other materials inside 3D prints is a challening task. Some studies [6, 9, 11] not only dealt with 3D printing using fabrics, but also how to extend it further by embedding fabrics into 3D prints. For example, Peng et al. [9] used conductive fabric to embed them into their soft prints, Hudson [6] developed 5 different embedding methods and Rivera et al. [11] approached new possibilities of rigid objects embedded with fabrics to further increase flexibility, as well as functionality. We will compare each method together with their resulting benefits and how to improve embeddings overall.

Peng et al. embedded circuits into fabric by using conductive fabric as a means. This is achieved by printing insulation layers between conductive layers, with connections between the conductive layers being made. Even though enabling new approaches to support interactivity in 3D printed fabric, this method has limitations. For instance, the connection between two layers has to be slightly larger than the heating disc in order to assure connectivity. As a result, creativity and the possibility of larger circuits is diminished, while also hurting the structure of the 3D prototype. Another problem arises through the printing method, where excessive fabric is removed at the end of the print (Figure 11). Through the use of conductive layers, the prototype may have shorts in unintended areas, destroying the prototype in the worst-case.

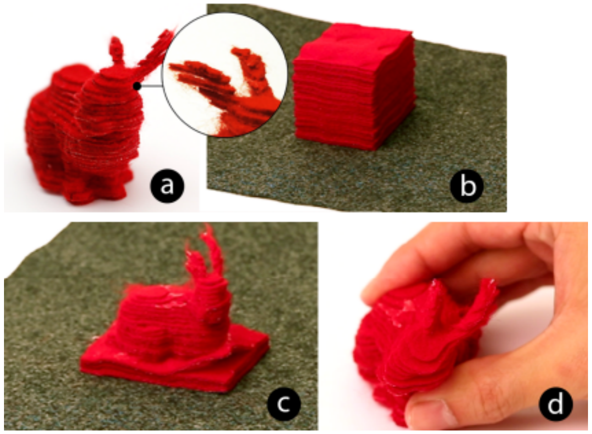

Figure 11: Removing excessive fabric of the final prototype [9].

Hudson had a different approach by using soft imprinted objects that support interactivity as the chassis, inserting interactive devices into them. While it is difficult to embed circuits using Hudson's method, different approaches dealing with different situations that extend the possibility of embeds are presented, unlike Peng et al., where conductive fabric was the only option.
One simple extension would be sewing embeds later on onto the chassis, enabling further possibilities like using conductive thread, made possible through the material properties provided by fabric. Using this method, it is fairly easy to connect components on the outside of the chas-

sis with the inside. However, this may be hard to accomplish if one does not know how to sew. If that is the case, other provided methods can be used to overcome such problems, namely being deep pocket embedidng, direct felt-over, capped pockets and nylon braid tunnels.

In comparison to Hudson, Rivera et al. used a technique to embed flexibility into rigid objects, rather than inserting rigid objects into fabric, creating different possibilities. The main weakness of fabric is that it is loose, limiting possibilities overall. To overcome this problem, plastic was added selectively into the fabric in order to enhance the fabric itself. This allowed the user to manipulate the fabric in such a way that one could choose where the fabric can bend or stretch. Further improvements such as selective adherence also allowed higher costumization of the fabric. The advantages that arise through their method is to accelerate the process of prototyping, reducing the overall duration of printing by using enhanced fabric.

Combining listed methods and possibilities together, one can say that it can benefit embeds and 3D print overall. As seen, the weakness of one method can be lifted with anothers'. With the printer created by Peng et al., two different kinds of fabric can be used for the prototype. Combining this with the selective stiffing of Rivera et al., one can only imagine the possibilities. One example would be to use the deep pocket embeding of Hudson and enhance it with selective stiffing, resulting in an overall better structure and solving issues such as keeping a distance to the embedded device in the pocket so that the needle does not damage it, since the pocket has an overall better structure. If we add the printer of Peng et al. into this combination, then the pocket can be easily sealed off and kept rigid by using selective stiffing as well.

Printing on top of fabrics

We have found that 3D printing directly onto fabric is possible. Whether there is good compatibility in terms of adhesion, warp or flexural strength depends greatly on the polymer materials and the fabrics. As Pei et al. found, the polymer PLA is most compatible with woven cotton. PLA is the less expensive polymer compared to ABS and nylon 645. Therefore, the majority of people should have access to both of it and be able to print directly onto fabric [8].
As simple as direct 3D printing on fabrics may sound, it is quite complicated to get the properties of both materials right in order to achieve the desired result.

A more complex approach can be found in the work of Goudswaar et al. [4], who had several criteria for the desired product of a mechanical push-button. Those criteria were high wearability, functionality, and reproducibility. They were successfully achieved using Lycra, which is a highly elastic nylon fabric, and the common PLA polymer.

As for the advantages of printing directly on the fabric, you can print the exact pattern you need on the fabric, as demonstrated in the work of Rivera et al. [11]. But the question arises why one would not just use a digital embroidery machine to not worry about polymer and fabric compatibility. So if it was just pattern printing, an advantage of using 3D printers for this remains to be shown.

However, Rivera et al. also demonstrated new properties that emerged only when combining a stiff and a soft material, such as selective stiffening or the creation of complex mechanisms like the folding lid. When combined with actuators and sensors, these techniques could lead to really interesting new products in the future. In this regard the use of fabrics in 3D printing clearly opens new possibilities.

We also see big potential in their idea of printing plastic shells onto fabric and folding the final object into form. A lot of plastic material can be saved by this approach, which reduces cost, time and environmental impact of the manufacturing process. This process is unfortunately not suitable for every application, as the level of detail that can be achieved using it is quite low. For simple shapes however, this is feasible and the look and feel could even be advantageous depending on the use-case.

A thing to consider when printing on top of fabrics is that certain materials may melt or even burn when they come in contact with the hot nozzle or filament. Goudswaard et al. [4] pointed this out as a reason why they chose to heat their filament to a maximum of 230℃, in order to prevent melting the underlying nylon fabric.

Conclusion

The usage of fabrics in the realm of 3D printing is still in its infancy, but already shows some promising results. The use of fabric as a printing material has a lot of hurdles to take before it is a viable alternative to other solution.

Using fabrics in combination with other materials could already be used today to solve specific problems, however there are no integrated solutions yet which can place the fabric onto the printing bed automatically. Creating fabric with an electrospinner in-place has been demonstrated, but the resulting fabric lacks important qualities of woven fabric.

Using fabrics in 3D printing can thus be seen as a very promising technology in the future, but it is mostly a research topic at the current state.

Future Work

The research field of using fabric embeds in 3D printing is quite new and thus there are a lot of open research questions. The printers we have seen which use pre-manufactured fabric as a printing material are very promising, but have some drawbacks which could be improved in refined designs. Both of the shown printers did not facilitate a second print head to combine the strengths of fabric and common 3D printing materials like plastic.

The use of fabric in a common 3D printer was shown, but the fabric had to be inserted manually in printing pauses. We have yet to see a printer that can do this automatically.

We see a lot of research potential in building on the design primitives proposed in the 2017 paper by Rivera et al. [11]. Combining the proposed shell method to save time with a print head that can cut custom-shaped fabric layers could be very beneficial for the printing time in certain applications. Also, the selective stiffness could allow for more sophisticated mechanisms than the one shown in the paper.

Printers that work with fabrics could potentially contain print heads that apply dye or special coatings on selected regions of the fabric, allowing to apply for example selective waterproofing or electrical conductivity.

To improve the adhesion between fabrics and filaments and reduce deformations in the printing process, research could be undertaken to either find especially good combinations of fabrics and filaments, or even go a step further and create new materials which are designed especially for the purpose of using fabrics in 3D prints.

In the case of the electrospinner by Rivera et al. they considered to dynamically change the strength of the magnetic field, in order to be able to print at higher layers than they currently can. This would open up a lot of new opportunities in what is possible with their prototype.

Considering the potential danger of melting the fabric when printing on it with hot filament, additional research could be undertaken to find more heat-resistant fabrics to print on, or filaments which can be applied by the nozzle on lower temperatures.

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