Exploring the Physical Design Space of 4D Printed Textiles

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ABSTRACT

3D printing on pre-stretched textiles, known as 4D textiles, offers the potential to create personalized shapes that transform from flat to spatial arrangements when released, combining both aesthetic and functional qualities. However, the lack of a defined fabrication process and the potential output possibilities of 4D textiles pose limitations on the accessibility of the technique, restricting the adoption by designers. This study aims to explore the physical design space of 4D textiles through a sample-making approach and extracting design parameters through a workshop with design students. Design guidelines are proposed for the creation of 4D textiles and further research directions based on expert opinion are proposed. The contribution of this study is the democratization of concrete guidelines for sufficiently fabricating 4D textiles using a consumer-grade printer, including documentation of various physical output possibilities, increasing accessibility of the fabrication method to other designers.

Keywords

4D-printed textiles; 4D Printing; Addititve manufacturing; Personal fabrication; Soft materials; Textiles

INTRODUCTION

The integration of fabric into the 3D printing process has garnered attention from researchers from a variety of disciplines. By embedding textiles into the 3D printing process, new output possibilities arise which opens up the design space of 3D printing, presenting promising prospects for advancements in personal fabrication.

One combination of fabric and 3D printing that receives particular interest is 4D-printed textiles. These textiles are produced by 3D printing specific structures on a pre-stretched fabric, which, upon release, morph into a spatial shape. This unique form-finding process results in outputs that can contain both aesthetic and functional qualities, therefore garnering a lot of attention from various fields ranging from fashion [1,2,11] to engineering [2, 14].

Despite the potential of the technique, the design space of 4D textiles still remains at a relatively early stage. Designers have proposed applications [1, 2, 11, 18], but commercial products have yet to enter the scene [16]. Furthermore, existing research primarily focuses on simulating the 4D textile form-finding process [2, 29, 32]. However, these simulations have not yet demonstrated completely accurate results [8] and are often inaccessible to the

Figure 1: Sample pool (1) of 4D printed textiles

public. Additionally, despite being an efficient method, these computational methods do not incorporate the physicality of the simulated outputs, which is a language that is crucial to designers. Moreover, means for successfully creating 4D textiles are not explicitly outlined in existing research, which hinders the adoption and further exploration of the technique by other designers. In light of these gaps, the aim of this research is to democratize knowledge pertaining to the fabrication process and different physical output possibilities of 4D textiles, aiming to address the research question: How can the fabrication process of 4D textiles be made more accessible to designers?

The method was split into three different segments based on sub-questions that were derived from the main research question. These were 1) How can we successfully fabricate 4D printed samples? 2) What is the physical design space of 4D printed textiles? 3) What is the value of the fabrication method of 4D printed textiles related to the industry? To address the first objective, the 4D textiles design space was explored through a first-person perspective sample making approach [12] using a consumer grade printer. Throughout this exploration, a pool of physical samples containing different geometries was explored and documented, optimizing the parameters for fabrication in the process.

To gain insights in the meaning of the samples, a workshop was conducted with four design students. During this session, samples were categorized based on overlapping characteristics. Furthermore, an evaluation with a 3D printing expert employed in the lighting industry was conducted to evaluate the value and applicability of the fabrication technique.

The sample making process culminated in the formulation of specific fabrication guidelines that constituted reliable print results for the creation of 4D textiles. A spectrum was deduced from analyzing the physical samples during the workshop, which ranged from amorphous shapes to well-defined structural shapes, including samples with bi-stable characteristics. Furthermore, evaluation with the expert highlighted both limitations and strengths of the current fabrication method, and provided possible directions for future research. Findings of this study increases accessibility of the 4D printed textiles fabrication method by allowing designers to build further upon the technique by utilizing the presented fabrication guidelines, drawing inspiration from the physical output possibilities, and considering future research directions proposed by the expert.

RELATED WORKS

3D printing on fabrics

Combining textiles and 3D-printing has gained significant attention from a variety of researchers. Adding fabric directly into the 3D printing process allows for the creation of outputs that both encompass the soft and dynamic properties of the fabric, combined with the wide variety of geometric outputs that a 3D printer is capable of producing. This permits the creation of outputs otherwise hard or impossible to attain using a 3D printer alone. The method therefore grants new design possibilities, whilst also significantly saving printing time and decreasing overall costs due to the mass availability of textile materials.

The multi-material method can be used for either the creation of soft materials ingrained with additional functionality or the production of rigid items with integrated flexibility. The former method garners a lot of attention from textile-heavy fields such as the fashion industry [1,2,11], whereby the addition of personalized structures to manipulate the appearance or functionality of the fabric is common practice. Using the additive manufacturing technique in this context also comes with the additional benefit of saving manual labor time, when comparing it to more traditional methods such as sewing. Furthermore, integrating the fabric's flexibility into the often-rigid 3D printed materials can also be beneficial as demonstrated in the research of Wagner et al. [31], whereby textiles and 3D printing are combined to create folding origami structures which use the fabric's properties as integrated hinges.

Despite the benefits of the fabrication method, the research topic is at a relatively early stage. Different design primitives of fabric-filament combinations were presented in the work of Rivera et al [25], showcasing different output possibilities including potential design applications. Furthermore, other work focuses on testing the adherence of different polymer-fabric combinations [17, 23, 26], which plays a crucial role to sufficiently apply the technique in actual design scenarios. These studies generally conclude that effective adherence can be achieved using some material combinations, but there is a lot of adherence variability. This topic, therefore, remains a field of ongoing research.

4D printed textiles

Four-dimensional (4D) printing is a relatively new research area first coined by Tibbits in 2012 [28]. It involves the printing of materials which contain properties that change overtime in a targeted manner after being triggered by an external stimulus. One sub stream of 4D materials are 4D printed textiles, which can be fabricated by printing structures on top of pre-stretched fabrics, which upon release, merge into a spatial shape in a unique form-finding process. In this scenario, the external stimulus is the release of tension, causing the shape to morph over a certain timeframe, hence the fourth dimension.

The 4D-textiles fabrication method contains many characteristics which are of particular interest to researchers. Adding the pre-stretched textiles into the 3D printing process allows for the creation of complex shapes which emerge from a simple planar geometry, which significantly decreases production time and material usage [16]. Additionally, the shape-morphing behavior yields potential for application in products containing self-assembling behaviour [21]. Furthermore, some 4D textiles also demonstrate bi-stability, meaning that the shape can be stabilized in two different orientations [11].

Currently, no commercially available products contain 4D textiles, but ideas for applications exist [16]. Fabriclick [11] explored the design space of bi-stable textiles, proposing a novel application of the 4D textiles as wearable physical buttons. Similarly, the application of bi-stability in soft actuators was also proposed in the study of Koch et al [16]. Furthermore, Application of 4D textiles can be observed in garments used in the fashion industry [7, 15] , and in 4D printed shoes [1]. The field of architecture also shows interest in 4D textiles as they allow for easy fabrication of curved or double-curved shapes, which are otherwise hard to fabricate using traditional methods [14].

Digital fabrication of 4D printed textiles

Fabrication of 4D textiles often involves the use of a fused deposition modeling (FDM) 3D printer combined with highly stretchable fabric such as Lycra Spandex [2, 14]. To achieve desired form changing behavior, flexible filaments such as thermoplastic polyurethane (TPU) with varying shore values are often used as filament [2]. These filaments offer the necessary flexibility to enable the shape morphing process. However, stiff filaments such as PLA can also be used, especially when printed in thin layers [18].

Multiple studies focus on computationally simulating the behavior of 4D textiles, by applying tools like finite-element-modeling (FEM) [29] or parametric tools such as the Grasshopper plug-in in Rhinoceros [2, 7]. The research of Pérez et al [24] presents results of a computational tool for the creation of 4D textiles Kichhoff plateau surfaces. Similarly, the research of Guseinov et al. [13] uses a computational tool for the creation of 4D textiles, enabling the creation of complex 4D textiles geometries. Altough the resultsof both studies look promising, both computational tools are inaccessible to the public. The article of Fields [33] does present an open source computational tool, but it's output possibilities are limited [3].

Whilst simulations are an efficient way of working, the models are not yet completely sufficient to describe the material's behavior [16]. Additionally, while simulation are useful for understanding how 4D textiles behave, they do not convey the tactile and visual aspects of physical samples which is a crucial aspects that designers use to inform their creative process [12]. Literature concerning physical sample making of 4D textiles is however limited. In the workshop of Co-de-iT, various samples are explored [4] in a Fablab environment. Similarly, the research of Kycia [18] explores the potential of self-forming textile structures for application in architecture. Both studies however present limited documentation and details regarding fabrication. The article of Fields [33], which explores the self-forming characteristics of 4D printed textiles including a few additional explorations, does share some details about the fabrication, but it's not sufficient to replicate the technique. This work builds further upon this gap by defining the fabrication method and its adjacent physical design space using accessible tools.

Figure 2: Sample pool (2) of 4D printed textiles

METHOD

Three methods were conducted to address each of the sub-questions that were derived from the main research question. The first objective was addressed through a first-person perspective sample making approach, optimizing the fabrication parameters of 4D textile samples throughout the process. The second objective was addressed by evaluating the physical samples together with four design students, aiming to ascribe meaning to the samples. Lastly, an expert evaluation was conducted to assess the fabrication method in relation to the industry.

First person perspective sample making

During the sample making approach [12], a plethora of physical samples with varying sizes and geometries were produced. The aim of the method was to explore the design space of physical 4D printed textiles and optimizing the fabrication method along the journey. Ultimately, the accumulated fabrication knowledge was synthesized into concrete design guidelines. Both physical and digital parameters of the samples were documented in a public GitHub repository, making them available for other designers for further exploration.

A consumer-grade 3D printer (Creality Ender 5 [6]) with a direct drive modification [5] was used to create the samples consisting of TPU 85A filament [9] and Lycra fabric (90% polyurethane, 10% polyester). Samples were printed with a 0.4mm nozzle and 0.2mm layer height. CAD models were made using Autodesk Fusion 360 [10] and sliced with the UltiMaker Cura slicer version 5.2.2 [30]. At the start of the exploration, a custom jig was constructed (Figure 3) similar to the one used in the research of Goudswaard et al. [11], enabling attachment of the pre-stretched fabric and proper alignment on the print bed.

To restrict the complexity and promote replicability of the sample making process, the design decision was made to produce samples containing fabric substrates that were either completely stretched biaxially (BI) or uniaxially (UNI) (Figure 3). Additionally, the varying shapes were constrained to basic geometries consisting of TPU beams of either 1x1x1 mm or 2x2x2 mm (l x w x h). Different fabric substrate sizes were explored, including a Big Circle (BC), Small Circle (SC) and Rectangular (RE) size (Figure 3).

Workshop with design students

To address the second sub-question, a workshop with four design students was conducted to analyze the characteristics of the samples, aiming to explore their meaning. The students were collectively instructed to group the samples according to overlapping characteristics. During this session, the audio was recorded, and notes were taken when participants would refer to a specific sample. These sample referrals were later added as annotations in the interview transcript. The transcript was analyzed using inductive thematic analysis.

Expert evaluation

An expert evaluation was carried out to assess the third sub-question. The participant that was included was an expert in 3D printing and worked as a product architect at a renowned lighting company. During this evaluation, the 4D printed textile fabrication technique was assessed through a semi-constructed interview (Appendix A) Topics included applicability of 4D printed textiles in the (lighting) industry, current strengths and limitations of the technique, and potential direction for further development. The audio during the evaluation was recorded, transcribed, and inductively thematically analyzed.

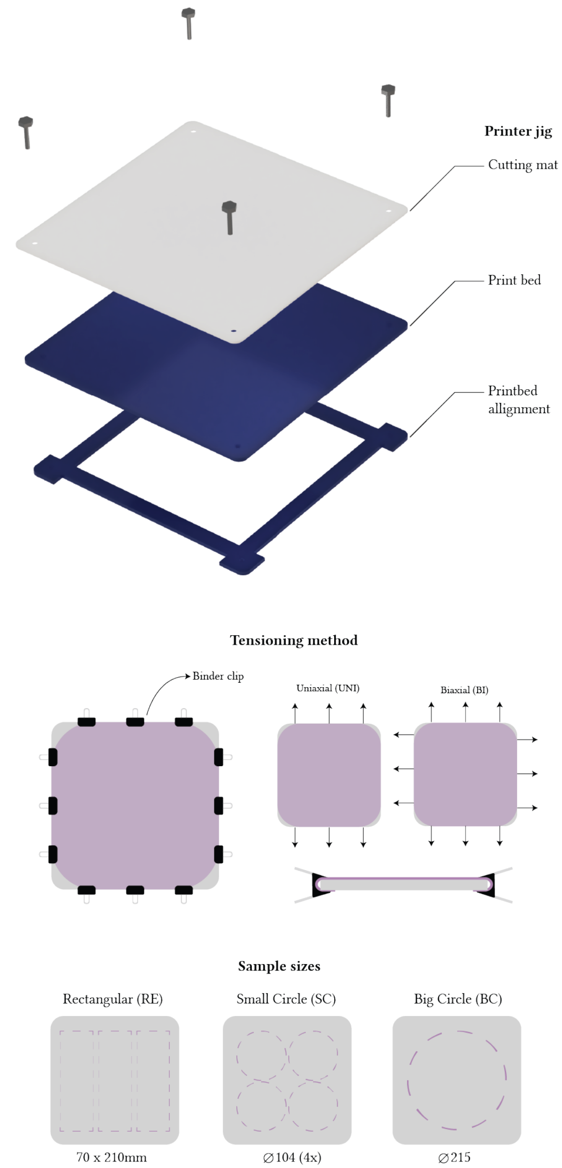

Figure 3: Illustration of the fabrication method used during the sample making process, including a custom jig, tensioning methods, and sample sizes

RESULTS

First person exploration sample making

The complete sample making process can be found in Appendix B. For this result section, samples representing milestones of various problems and proposed solutions are presented.

The first problem that occurred during the first-person exploration were adherence issues between the filament and fabric (Figure 4A). To address this problem, the Z-offset of the printer was configured to approximately 0.1 mm for the first layer. This configuration allows the printer to *"push"* the polymer into the fabric, which resulted in better adhesion.

Due to the lowering of the z-offset, clogging of filament in the nozzle became an issue. The filament would clog in the extruder drive because of the increased pressure caused by decreasing the print height, which lead to failed prints (Figure 4B). To address this problem, a drive modification was printed and mounted on the 3D printer [8] which prevented this clogging issue.

Despite previous printer modifications, adherence remained a problem (Figure 4C). Although the bond did increase, the filament would still occasionally detach from the fabric. To address this issue, the geometry of the first layer was first *"charred"* into the fabric, by printing the first layer without extruding filament with a 0 mm z-offset. After this initial layer, the print would pause and the filament would be loaded back in, after which the print would be resumed. This fabrication step seemed to significantly increase the adherence strength.

Unwanted leaking of filament (Figure 4D). during travel time of the nozzle, known as stringing, became the next issue. To resolve this, the setting *"combing mode"* was turned to all and *"avoid printed parts when traveling"* was deselected in the Cura slicer. These setting instructs the printer to only travel above printed parts, preventing stringing in between the printed geometry.

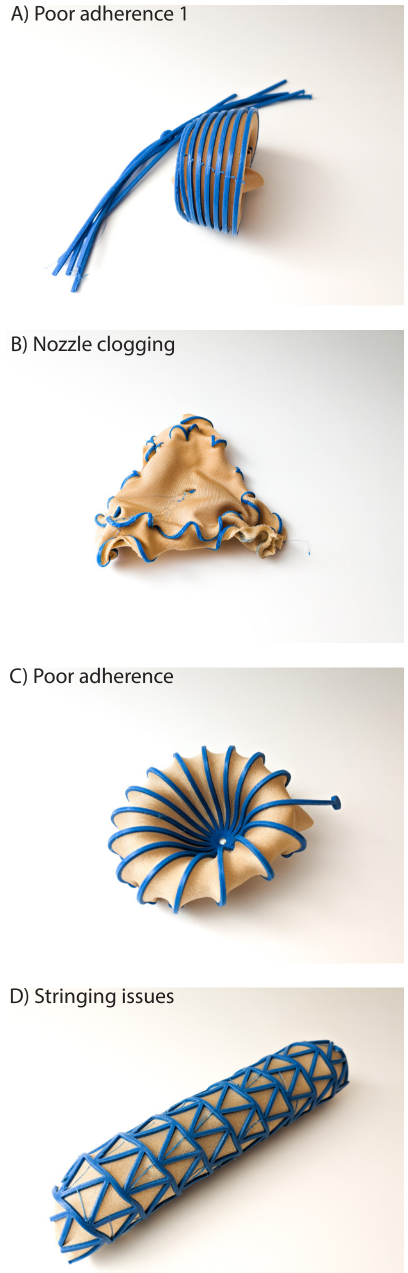

Figure 4: Sample milestones including A) Adherence issues 1 B) Nozzle clogging C) Adherence issues 2 D) Stringing issues

Adjusting the combing settings resolved stringing for the continuous shapes, but it did not for geometries that contained separated beams as the printer couldn't prevent travelling between the printed parts. The problem was initially addressed by putting a complete border around the shapes, but that greatly impacted the final shape (Figure 5 E.1). So, instead, a small border of a single layer height (0.2 mm) was printed around the shape instead (Figure 7B). This allowed the printer to travel over the thin outside border, which would later be cut off from the sample. This resolved the issue of stringing, without having to make significant changes to the discontinuous geometries. Additionally, by printing a thin border around the sample, it became a lot easier to cut out the shape.

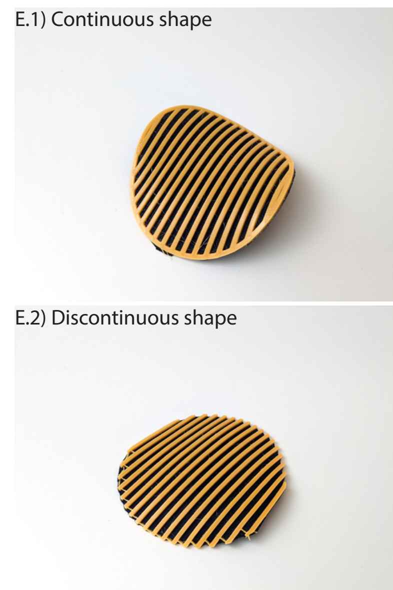

Figure 5: Stringing issues in continuous geometry (E.1) compared to discontinous geometry (E.2)

The final sample (Figure 6) of the exploration was aimed at testing all the accumulated fabrication knowledge into one conclusive 3D print. The sample consisted of disconnected beams with increasing thickness ranging from 0.32 mm to 4.8 mm. The resulting output was successfully fabricated and showed strong signs of adherence, whilst showing no signs of stringing.

Figure 6: Final sample of the sample making process containing beas with varying thickness

Final design guidelines

Based on the knowledge gathered during the first-person sample making approach, fabrication guidelines for the creation of 4D textiles were formulated.

1) Jig: Although pre-stretching and attaching the fabric onto the original print bed can be done, it is very impractical. It would be difficult to avoid putting a lot of pressure on the print bed, especially when maximally stretching out the fabric. Therefore, using an external jig that can fit the print bed is more desired. This allows for pre-stretching of the fabric prior to installing it on the printer bed. This jig can be fabricated using a laser cutter and acrylic material. The downside of using a jig is that no bed heating can be applied, but this did not seem like a necessary parameter.

2) Hardware: A direct drive [5] and extruder modification [8] are necessary hardware adjustments which allow for printing of flexible filament without nozzle clogging. These attachments can be printed with standard PLA filament.

3) Slicing: Combing setting should be turned to *"All"* and *"Avoid Printed Parts When Traveling"* should be deselected, which instructs the printer to only travel over already printed parts, preventing the filament from stringing. For discontinuous models, a thin border of 0.2mm should be modelled around the shape which connects the separate parts, allowing for the nozzle to travel over the thin border, rather than traveling in between different segments. The border can later be cut off from the sample.

4) Printing process: To ensure proper adherence between filament and fabric, the first layer of the geometry needs to be charred in the fabric with a z-offset of 0 mm and a nozzle temperature of 210℃. Higher temperatures would tear up the fabric. The Cura Post-Processing Script Pause at Height is best used for this purpose, which enables instructing the printer to pause after printing the first layer. After charring, the filament can be loaded back into the extruder, and the print can be resumed. The first layer should be printed with a 0.1 mm z-offset and with a nozzle temperature of 230℃, allowing the printer to push the filament into the fabric. The rest of the print can continue according to standard print protocol, printing at a layer height of 0.2 mm.

Full slicing details including all physical sample models are documented for review in the open source GitHub repository [20].

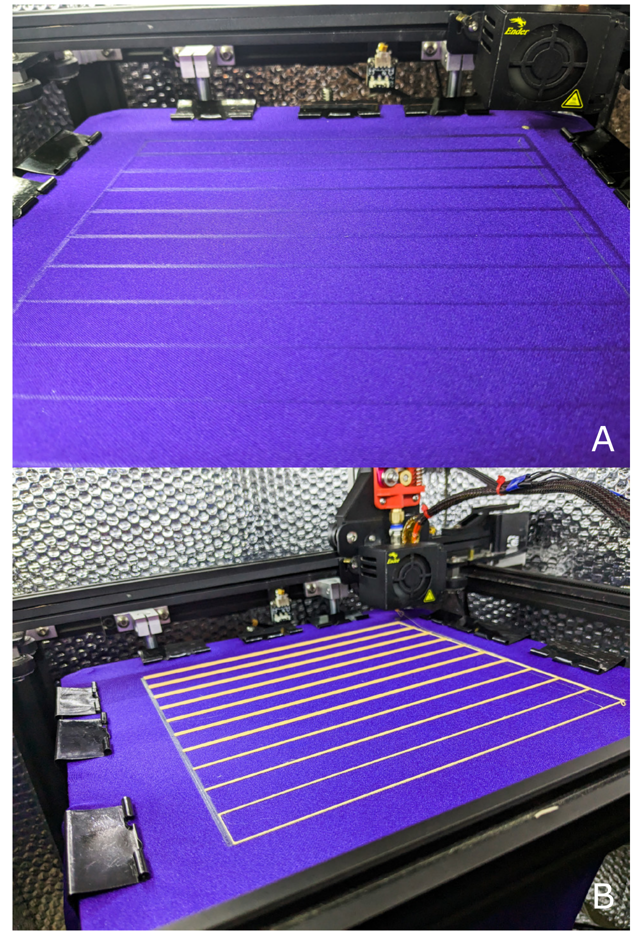

Figure 7: Making of the final sample including A) charring of the material and B) The printing process

Workshop with design students

Analysis of the samples by the four participants resulted in five different sample groups: Chaotic, unpredictable, cylinder, bent, crescent, and bi-stable shapes (Figure 8). Themes for analysis were constructed based on these formulated groups. By further analyzing the interview transcript with the included sample annotations, overlapping traits across the different sample groups could still be noted. From these overlapping traits, a spectrum was deduced ranging from amorphous shapes to well defined shapes. The former contains shapes with minimal structure and unpredictable shape morphing behavior (e.g., the chaotic and unpredictable shapes), whereas the latter consisted of sturdy shapes that have a clearly defined end shape (e.g. bent, crescent and cylinder shapes). Amongst the spectrum, a bi-stability range was added, containing shapes that contained two stable orientations.

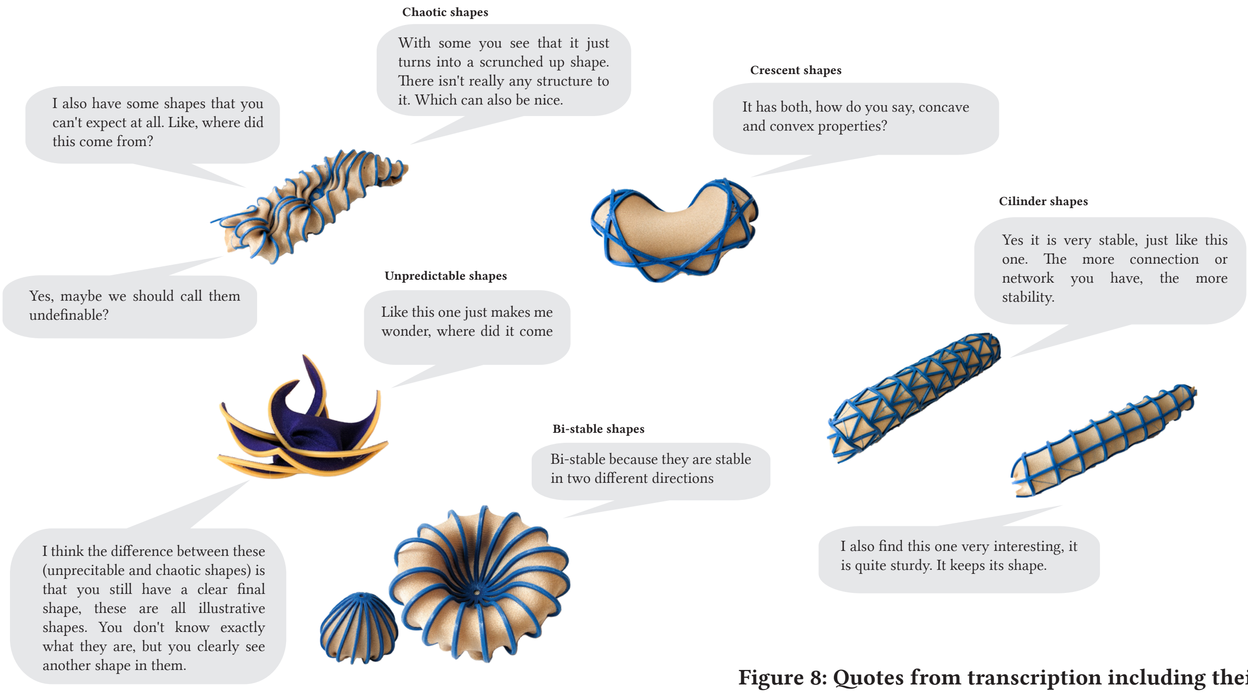

Figure 8: Quotes from transcription including their sample annotation and sample group

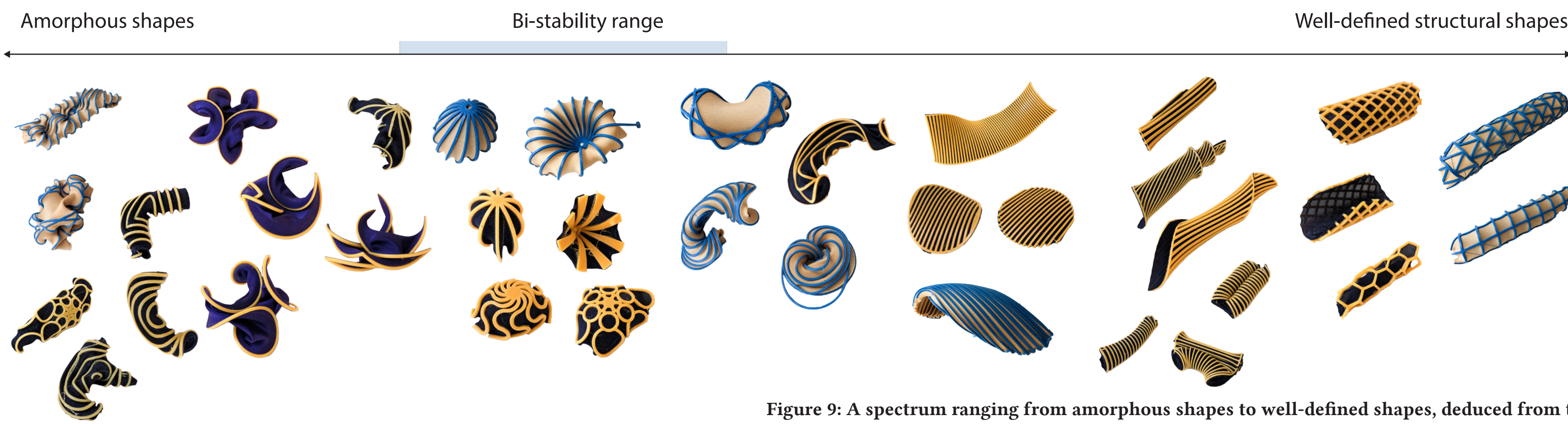

Figure 9: A spectrum ranging from amorphous shapes to well-defined shapes, deduced from the workshop transcript

Expert evaluation

Samples were presented to the expert including a speculative design (Figure 10) consisting of a sample with an integrated flexible led light (n00ds, Adafruit (27)). Themes that were derived from the interview transcript included the following: Aesthetics, Strengths and limitations of the fabrication method, and directions for further development of the fabrication method.

Figure 10: 4D printed sample with integrated flexible LED

Strengths and limitations

When asked about flat packaging:

"Yes, that's definitely beneficial. Especially concerning print speed, right? Normally it will take a long time to print a shape like that, but now it can be done very fast, that's a benefit."

"Transportability and assembly remain an issue in any industry, not just the lighting industry, which is much less the case when using 3D printing. Whenever one part cannot be supplied, the whole manufacturing process will stall. This is much less the case when using a 3D printer as it decreases that reliance on suppliers. The ability to flat package these objects is also a big win in terms of transportability. You can just print it flat, add some additional 3D printed components and package it in flat orientation. Then you get a product that is both easy to transport and requires minimal external parts."

When asked about the fabrication method in its current state:

"Yes, you can clamp the fabric on it and then you can print well, so you could continue like this. You can make small batches, a thousand products approximately. You would have to do a lot of manual work. But it could potentially be done."

Interpretation

The expert emphasizes the flat-packaging ability of 4D printed textiles, as it hold clear benefits concerning increasing transportability of the product whilst reducing reliance on external suppliers for assembly. The fabrication method in its current state is suitable for producing small to medium batches of product, but it would require a lot of manual work.

Aesthetics

When asked about applicability of the samples in the lighting industry:

"For us it's mainly the aesthetics that we really like. It looks decorative and it's interesting that you do lighting. I also find those n00ds interesting." "It's that decorative aspect that you want to emphasize, yes, that it looks like a flower and contains bistability."

"You can't be at the Dutch Design Week with it yet, but it is possible, if you focus on refining the edges and look at different fabrics, because these are not the most attractive, perhaps even better ones can be found."

"Right now, it's all a bit bulky, if you look at new generations of printer, the quality is a lot higher and they are a lot faster. But you may not have had that machine available. But there are now machines that finally make it a little more beautiful. If something needs to be round, then it will be round and when it needs to be square, it is square. Then the product is finished immediately after printing. But that its not to say that your project is not good, right? It will all be fine with the next generations of 3D printers."

"What I think in 4D printing is that we always make relatively little use of the height in printing. The structures are kind of 2D and there is never a height difference. Why? Why aren't there any fins or something, or dots. Could be interesting to see what that does."

Interpretation

In this dialogue, the expert emphasized the aesthetic and decorative properties of the 4D textile samples. However, in its current state, the aesthetics of the samples do require refinement in terms of material choice, and a better finish of the edges of the sample is desired. Additionally, the expert proposes 3D-printing different textures and going up in height as a direction worth exploring. Furthermore, the print quality could be increased using the new generation of 3D printers that is currently emerging.

Further development of the fabrication method

Concerning industrialization and upscaling of the fabrication method:

"Automating the stretching of textiles and then printing is difficult. Then you may have to make another jig. That

is a lot of work, so you must think very specifically."

"But textiles can be very large though, right? You can print one part, then move it a bit, print again. Then you can print large textiles. You could also print on roll of textile which cycles through the printer. That's a kind of industrialization in itself. You just roll the fabric through while printing."

Interpretation

The expert proposed methods of industrializing the fabrication technique, either by cycling a roll of textile through the printer, or by printing locally on segments that are part of a large piece of textile.

DISCUSSION

The aim of study was to enhance accessibility of 4D printed textiles for designer, encompassing three main objectives: 1) Formulating design guidelines to replicate the technique with a consumer-grade printer 2) Exploring the physical output possibilities of 4D textiles, and 3) Evaluating the fabrication method with an expert in the industry.

The sample making process resulted in concrete fabrication guidelines for printing 4D textile samples. Modifications to the printer were made and slicing setting were optimized which resolved clogging, adherence, and stringing issues. Moreover, findings of the workshop with design students suggest a diverse range of physical output possibilities concerning 4D printed samples, ranging from amorphous shapes to well-defined structural shapes, including shapes that exhibit bistability. Expert evaluation emphasized the value of the fabrication technique in terms of its unique manufacturing capabilities and aesthetic output possibility, but the need for industrialization and aesthetic refinement became apparent.

The fabrication guidelines that were presented are aimed to make the 4D printed textile fabrication method more accessible for designers. These guidelines enable designers to replicate and further expand on the technique using traditional FabLab tools. Regarding the sample making process, clogging of the nozzle is a common problem when printing with flexible filament, which is often addressed by upgrading the entire nozzle [19]. Findings of the exploration suggest a printable alternative [8], which can resolve the problem without the necessity of costly upgrades. Furthermore, charring the material seemed to significantly increase the adherence between the fabric and filament, which is an adherence parameter that has not been researched in any of the adherence-related studies [17].

Documentation and analysis of the samples with other design students provides a physical overview of possible 4D printed textiles outputs. This library, which can be found in the GitHub repository [20], presents designers with various physical examples with structural variations. This resource serves to illustrate possible shape transformations that can be achieved with 4D printed textiles, which designers can draw inspiration from to inform further design research in this domain.

The expert emphasized the aesthetic attributes of the 4D printed samples, highlighting their suitability for lighting applications. Additionally, the ability to flat-package the 4D printed textile has significant potential to increase the transportability of products, whilst decreasing reliance on external suppliers. The expert proposed a method for scaling the fabrication method, which is in accordance with one of the design primitives, printing segments of a larger piece of textile, presented in the research of Rivera et al. [25]. By rolling the fabric through the printer, a continuous shape could be fabricated, which could prevent the emergence of gaps when printing different segments of a larger textile, which was presented as a limitation in the study of Rivera et al.

Limitations

The design guidelines that are presented were based on the hardware and software described in the method section. These fabrication guidelines might not be applicable to other machinery, which could impose different fabrication challenges. Additionally, the fabrication method works well for the type of shapes that were presented, but they merely represent a tiny portion of the potential output possibilities that a 3D printer can produce. Therefore, other fabrication problems can emerge that were not addressed in the sample making approach. For instance, printing discontinuous shapes that cannot be linked up in the periphery of the print will most likely result in new stringing issues and, similarly, the expert's proposition to print beams with varying heights might do so as well.

The results of the workshop provided some insights into the output possibilities of 4D printed textiles in terms of materiality, but the limited sample pool might illustrate a biased result. A larger sample pool with more shape variability might have led to a different outcome. Additionally, including more designers and conducting more workshops would allow for the accumulation of more data and the possibility for cross-examination, which could lead to more substantiated results.

Recommendations

Future work should focus on further exploring the physical design space of 4D textiles, expanding the sample library with additional shape morphing characteristics that can further inform design processes. Additionally, shapes with varying heights and different material combinations should be explored to further define the design space. Furthermore, A peel-off strength test should be conducted to assess the influence of charring on the adherence strength of the fabric and filament.

Improvements regarding the aesthetics of the samples, which were coined by the expert, can be further built upon. These aesthetic improvements consist of increasing the print quality, which could potentially be achieved with the newer generation printers, and finding methods to refine the edges of the samples. Furthermore, means for enhancing the fabrication method should be further explored to increase the automatization and scaling aspect. A belt printer could potentially be modified to accommodate for this, which could allow for the creation of larger sample sizes.

Conclusion

The aim of this study was to increase accessibility of the 4D printed textiles through formulating fabrication guidelines, exploring physical output possibilities, and evaluating the fabrication method with an expert. Concrete design guidelines were constructed based on a consumer-grade printer and FabLab equipment, aiming to lower the threshold for adoption of the technique. Various physical 4D-textile shapes are presented which designers can draw inspiration from to further inform future design processes. The expert evaluation highlighted the aesthetic appeal of the samples, and the potential of the fabrication technique to reduce printing time, increase transportability, and decreasing reliance on external suppliers. Overall, these findings aid in making the 4D textile fabrication technique more accessible to designer, by allowing replication of the technique using consumer-grade tools, providing insights into the different physical output possibilities, and providing future research directions derived from expert opinion.

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APPENDIX A: SEMI-STRUCTURED INTERVIEW WITH EXPERT

Main objective:

Assess the value of the fabrication method related to the industry, and analyze for further research direction.

Semi-structured interview:

0) Please describe your field of expertise

1) Do you consider 4D printing a technique that is applicable to your field of expertise, or other fields? And if so, what are the characteristics that you find valuable?

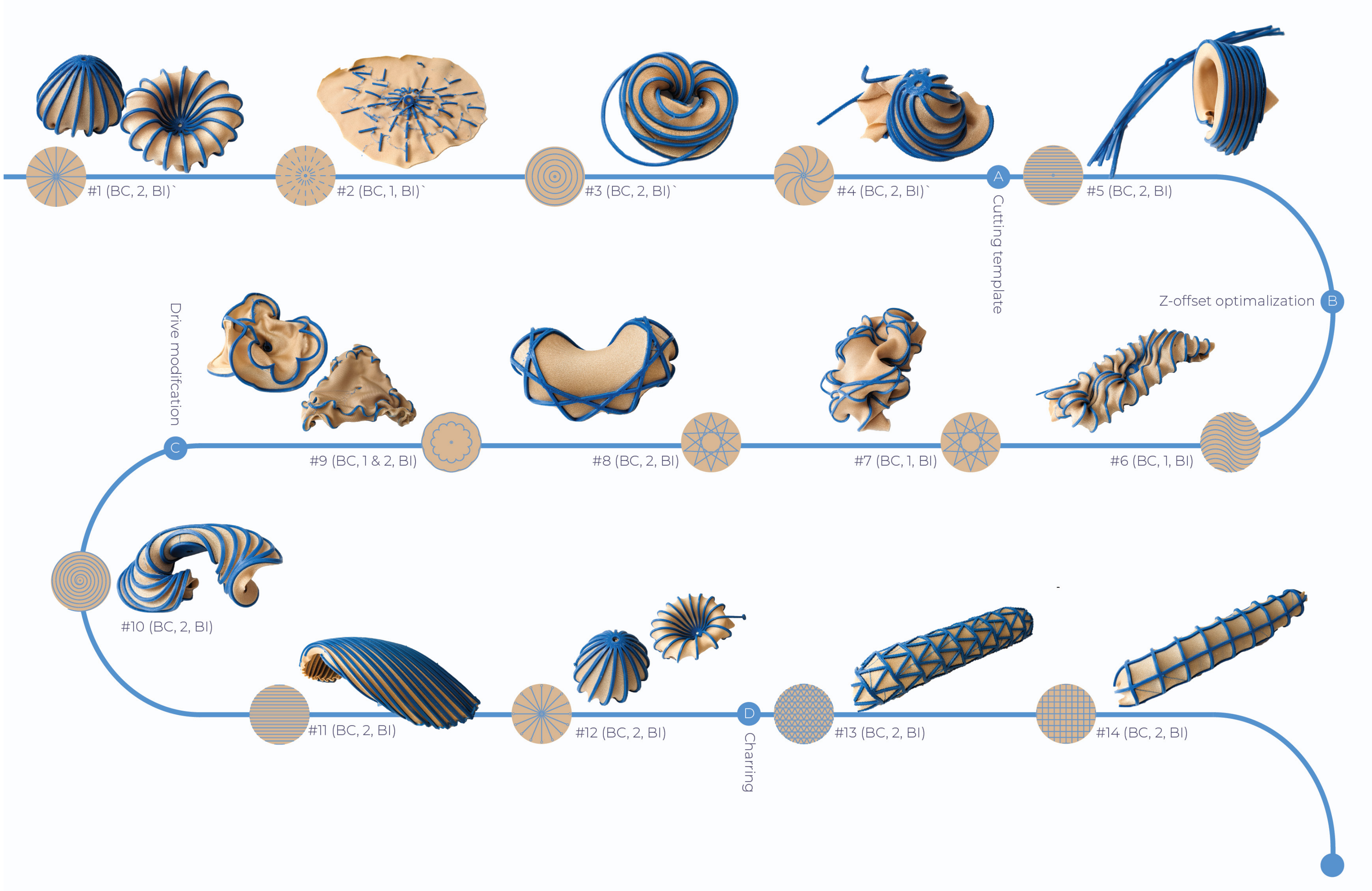
2) What do you think about the characteristics of the fabrication method?
(e.g. shape morphing capability, less material usage, 3D printing, etc.)

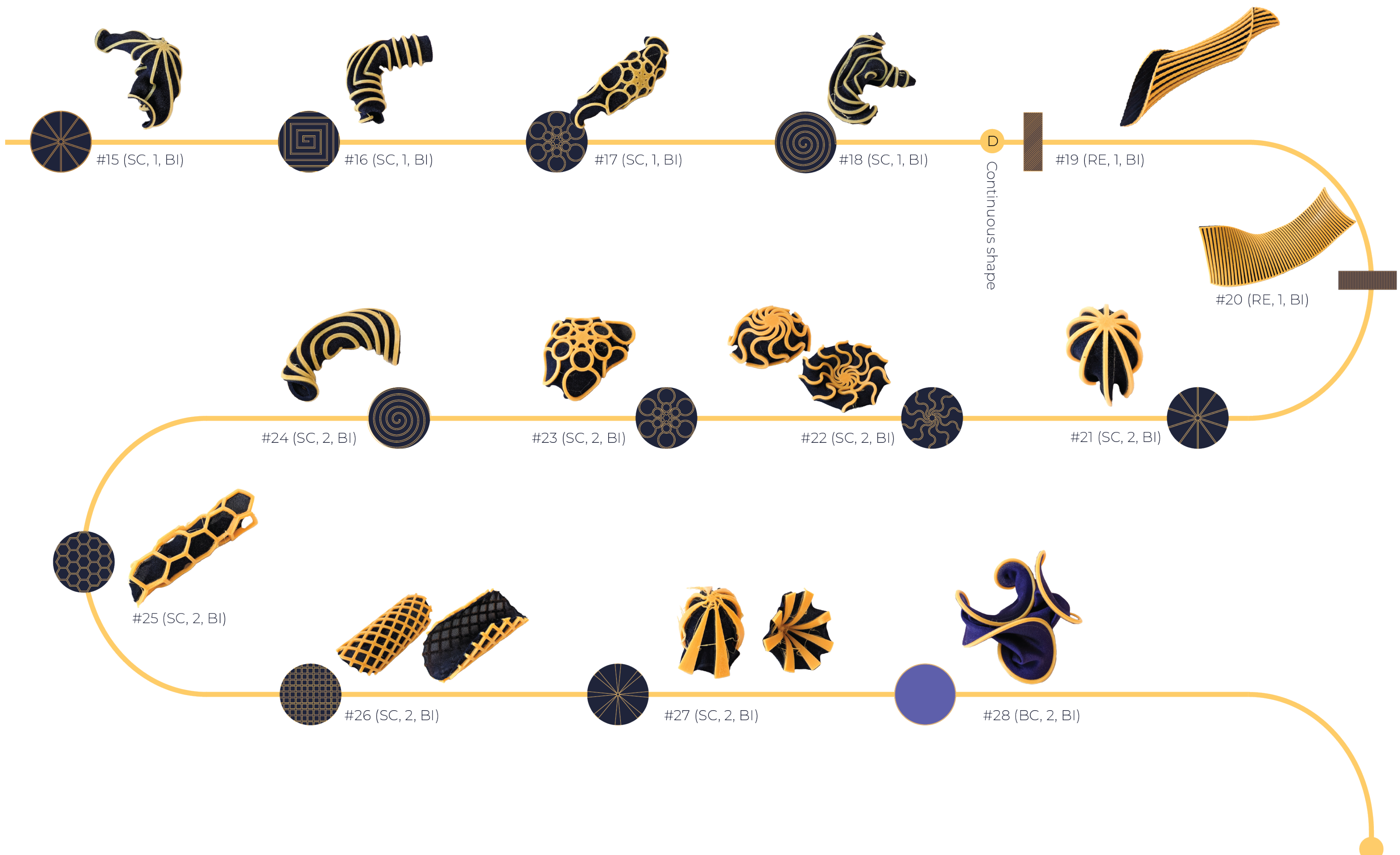
What elements of the fabrication method do you see as a limiting factor?
(e.g. the scale, manual labor, the outputs)

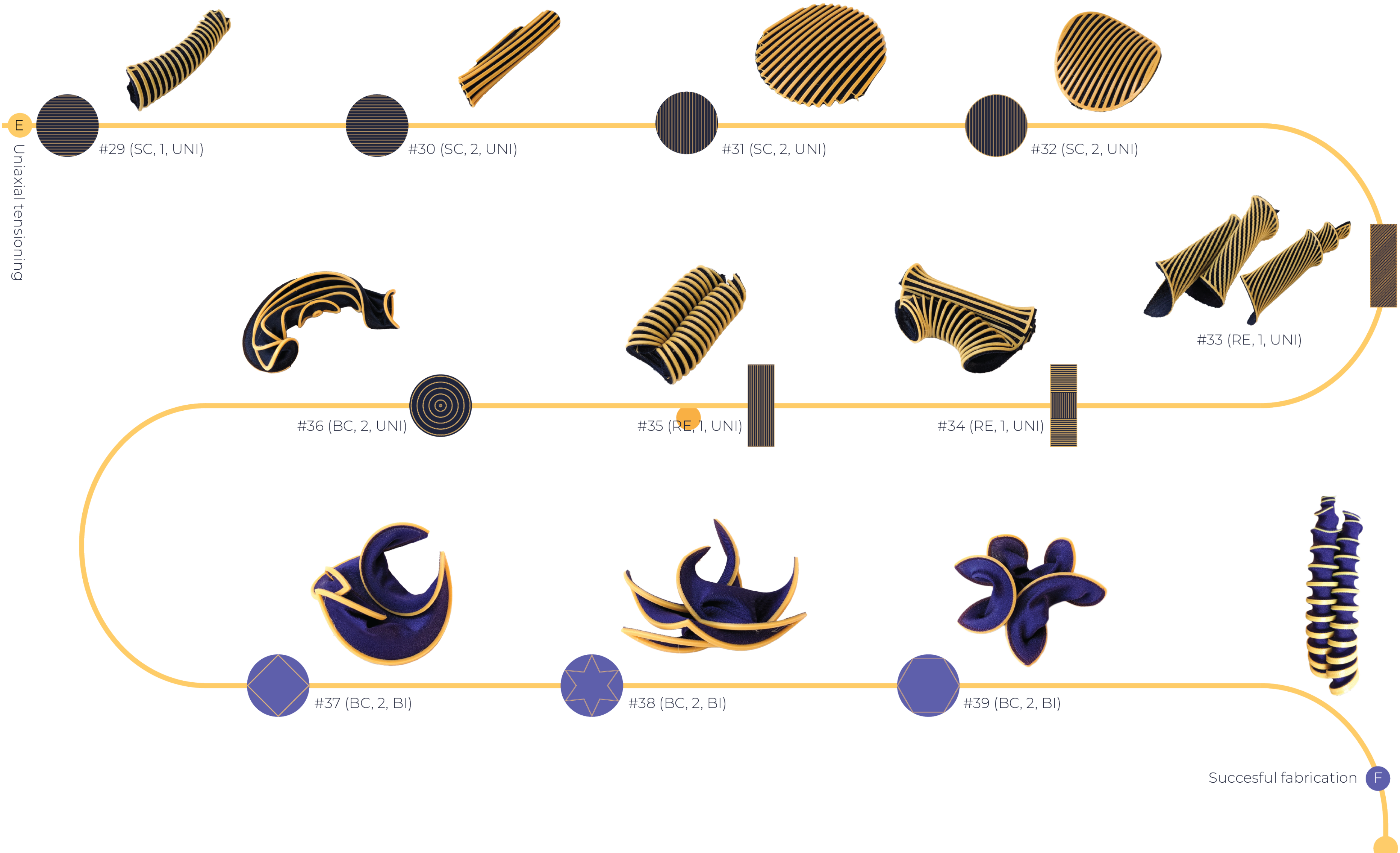
What possible future directions can be undertaken for further development of the technique?

(e.g. industrialization, better finish, reliable production)

APPENDIX B: SAMPLE MAKING PROCESS




#15 (SC, 1, BI)
#16 (SC, 1, BI)
#17 (SC, 1, BI)
#18 (SC, 1, BI)
D
Continuous shape
#19 (RE, 1, BI)
#20 (RE, 1, BI)
#21 (SC, 2, BI)
#22 (SC, 2, BI)
#23 (SC, 2, BI)
#24 (SC, 2, BI)
#25 (SC, 2, BI)
#26 (SC, 2, BI)
#27 (SC, 2, BI)
#28 (BC, 2, BI)


E
Uniaxial tensioning
#29 (SC, 1, UNI)
#30 (SC, 2, UNI)
#31 (SC, 2, UNI)
#32 (SC, 2, UNI)
#33 (RE, 1, UNI)
#34 (RE, 1, UNI)
#35 (RE, 1, UNI)
#36 (BC, 2, UNI)
#37 (BC, 2, BI)
#38 (BC, 2, BI)
#39 (BC, 2, BI)
Succesful fabrication
F