Four-dimensional Printing on Textiles Evaluating digital file-to-fabrication workflows for self-forming composite shell structures

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This design-led research investigates the development of self-forming wearable composite structures by printing embossed patterns out of flexible filament on pre-stretched textiles and releasing the stress after the printing has been completed, whereby time becomes the fourth dimension of the printing process. In particular, the study presents and compares three methods of 'file-to-fabrication' techniques for generating self-forming textile shell structures: The first is based on modified geometrical patterns in relation to curvature analysis, the second on printed patterns related to their stress line simulation and the third on an analysis of the anisotropic shrinking behaviour of stripe patterns. The findings emphasize the advantages and challenges of each method as well as present a comparative table chart highlighting the relationship between material properties, pattern geometry and the formal vocabulary of the composite shells.

Keywords *4D printing, additive manufacturing, textile wearables, digital materiality.*

INTRODUCTION

At the end of the 20th century, debates and developments which significantly changed the character of geometry gained momentum. By 1970, Frei Otto pioneered this debate with his research on doubly curved fabric structures. Otto's design and form-finding process were strongly relying on physical models, rather than computational methods. Having developed a large range of innovative structures, by the early 1990s, Otto et al. (1995) declared:

> 'Our times demand lighter, more energy-saving, more mobile and more adaptable, in short, more natural buildings, without disregarding the demand for safety and security.'

In the early 2000s, others such as Brown and Rice (2001) at Arup, focused on computational methods and techniques which they were applying for material innovation stress analysis and form-finding. Those developments continued in the 2010s, with membranes and textiles being used successfully in building construction in the form of roofs, facades, pneumatic structures and tents. In our times, the rapid development of emerging technologies such as additive manufacturing and developments in material science are enabling designers to consider further innovative solution synergies expanding their applicability to a wide facet of complexity and materiality such as plastics, concrete and metals. While additive manufacturing technologies have been experiencing rapid development in the past two decades, the notion of four-dimensional printing only appeared in 2012, according to Wu et al. (2018). The term describes the process through which a 3D printed object transforms its shape and structure over the influence of environmental parameters (e.g. temperature, humidity, light) or material properties (e.g. digital shape memory or stress relaxation), whereby the fourth dimension of the printing process becomes time. In this research, the fourth dimension is applied after the filament has been printed onto the flat, stretched textile, as the artefact is released from its print frame and starts shaping in the third dimension within less than a minute.

In continuation to previous work by the authors on '3D printing of elastic fibre patterns on pre-stretched textiles' (Agkathidis et al. 2019), 'architectural hybrid material composites, computationally enabled techniques to control form generation' (Berdos et al. 2020) and Computational Design of Self-Actuated Surfaces by Printing Plastic Ribbons on Stretched Fabric (Jourdan et al. 2022) this paper investigates the possibilities arising in shape, material properties and geometry of objects produced, by printing a flexible material (TPU 95A) onto pre-stretched elastic fabric (lycra) using Fused Deposition Modelling (FDM).

In particular, three different form prediction / form-finding methods were applied as described by Agkathidis et al. (2019), Berdos et al. (2020) and Jourdan et al. (2022) and tested their effectiveness in predicting the desired shape and their suitability and limitations for producing particular geometries. Furthermore, the three methods are assessed and verified by using an UltiMaker 2+ 3D printer whereby printing took place directly on the fabric. Consequently, the following research questions were investigated:

- Which of the three proposed methods assessed here is more effective in controlling and predicting the form and performance of hybrid panels composed of flexible pattern fibres printed onto pre-stretched textiles?
- How do the material properties of the individual components - the textiles and the pattern fibres - contribute to the properties of the composite material?

To answer the above questions, a set of design-led, physical experiments are conducted using the three different form prediction methods utilising the same 3D printer and textile materials by developing a set of composite wearable prototypes. The findings were analysed and compared to enable conclusions.

BACKGROUND AND LITERATURE

The study began by looking into the related work of other researchers to inform our research of the latest developments in the field. In their research, Joshi et al. (2020) presented various active materials, 4D printing and shape memory techniques, however, their approach was mostly emphasizing the field of structural engineering as they were focused less on design. Cheng et al. (2020) and Cheng et al. (2021), describe the development of a fused granular fabrication method capable of producing 4D printed meta-structures, out of biocomposite material, which can change their geometry from flat to curved in relation to the environmental humidity. However, their work is using a completely different material pallet, than the ones examined in this paper.

Meyer, Dopke and Ehrmann (2019) investigated the adhesion of 3D printed polylactic acid (PLA) on textile fabrics using the FDM technique, similar to Redondo et al. (2020), who also researched the adhesion of 3D printed PLA samples on fabric by using the FDM technique. Even though both works provide valuable insights into the material properties and behaviour of PLA printed on fabric, they are neither examining the formal behaviour of the 3D printed objects nor their capability to change in time.

'Additive Manufacturing and Textiles' by Sitotaw et al. (2020) broad overview casts light on various 3D printing techniques related to textiles, however, it was mostly focused on understanding material and technique properties rather than introducing novel materials and methods, while Giglio et al. (2021) focus on 3D printed PLA fabrics rather than on composites of PLA structures printed on textiles.

The prototypes produced in the workshop by Erioli and Naldoni (2017) explored the possibilities in form generation by printing PLA patterns on pre-stretched textiles. A similar technique was previously presented by Guberan and Clopath (2016) in their 'Active Shoes' project, where a specific geometry printed on a pre-stretched textile allowed the creation of a controlled and predictable shoe. However, in both cases, their investigation appears to emphasise artistic over empirical qualities, without incorporating simulation methods and form-prediction mechanisms.

In their article 'Printing on Fabric Meta-Material for Self-Shaping Architectural Models', Jourdan et al. (2021) described a systematic method to design deployable textile shapes by using a star-based pattern system. They also developed a novel technique to simulate and predict the final shape of the models, which they printed on lycra with TPU.

In addition, Koch, Schmelzeisen and Gries (2021), gave an overview of recent techniques for the generation of 4D textiles made by additive manufacturing on pre-stressed textiles, offering a valid database for categorising, evaluating and assessing the techniques and methods of our research.

In their 'FabriClick' article, Goudswaard et al. (2020) showed a method for interweaving push buttons into fabrics by using FDM and digital embroidery techniques. Even though they were achieving similar effects as described in our research, they don't seem to be using form prediction techniques such as stress line simulation and curvature analysis in their design process. A similar approach is described by Kycia (2019), in the research on 3D printing on pre-stressed fabrics to create textile composites and explore their potential applications as building envelopes. Kycia has explored PLA, as well as polyolefin filaments on smaller as well as scale prototypes. Kycia showed rather simple, hyperbolic paraboloid geometries, without presenting any computational, form predicting methods. Finally, the research described by Aldinger et al. (2018) in the 'Tailoring Self-Formation' paper has common ground with our work. However, finite element analysis appears to be their main tool for form prediction. In their material studies, carbon fibre rods were knitted into the fabric and helped to better control the self-formation geometry, which is a different fabrication method than using FDM to deposit filament on the textiles to produce composite shapes.

The conclusion deriving from the literature review on similar research is that 4D printing on textiles is an up-and-coming research field that is currently being investigated by many research groups around the world. However, even though researchers have applied various methods and techniques of 4D printing and form prediction, our research appears to offer an original approach to the field as it is comparing a combination of methods not described by any of the researchers.

MATERIALS AND METHODS

As previously described, three different form-prediction methods were applied and tested for developing pattern geometries which were then 3D printed on pre-stressed textiles. By releasing the newly composed prototypes, the objects should self-form into the desired wearable shape. The first two methods were developed using parametric tools (Rhinoceros and Grasshopper). In particular, Method 01 is based on utilising Mean curvature analysis of

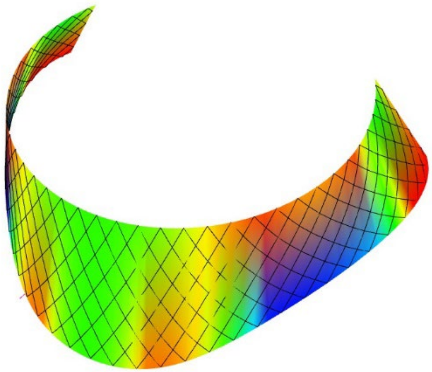

Figure 1
Method 01 diagram indicating the modified geometrical pattern following the Mean curvature map

the digital design model and adjusting geometric patterns on it by using an algorithm incorporating the Panelling Tools plug-in for Grasshopper (Figure 1). The modified pattern is then flattened, embossed and printed onto the pre-stressed textile.

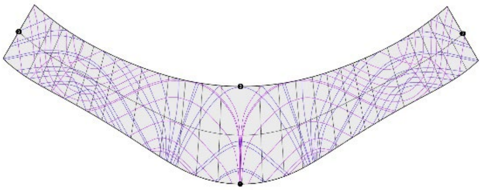

Figure 2
Method 02 diagram illustrating the stress lines of a curved surface.

Method 02 is based on an algorithm incorporating the Karamba structural simulation plug-in for Grasshopper, capable of conducting stress line simulations on the desired, digital design model (Figure 2). The stress lines were rationalised and converted into a pattern which was then flattened, embossed and printed onto the pre-stressed textile.

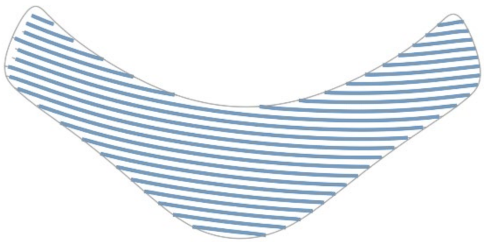

Figure 3
Method 03 diagram illustrating the linear pattern generation process.

Method 03 is based on careful geometric analysis of the surface model in relation to the flat pattern to be printed: the key idea is that by knowing the amount of stretch applied to the fabric and how much it is covered by plastic we can infer the deformation that the initially flat material will undergo. By continuously varying the spacing between printed lines, the algorithm is able to control the distortion induced by going from the flat state to the deployed surface and therefore can accommodate developable as well as doubly-curved surfaces. Moreover, the method automatically computes the thickness of plastic needed to reproduce a given curvature, which makes it comparatively easier to obtain results that are close to a given target model (Figure 3).

All three methods were tested by conducting one experiment, where three of the same wearable objects (necklaces) were designed and fabricated. In order to proceed with the 3D printing, the textile was placed onto a rectangular frame, fixed on two sides and then stretched on the other two sides. Marking a segment of length l_0 on the unstretched textile and stretching it to a length l, we compute the stretch percentage as $100\ (l - l_0)/\ l_0$.

The design experiments (01,02,03) measured the displacement between digital and physical models, thus the effectiveness of each method was verified, as well as identified the parameters which may influence the form prediction/generation. The study utilised an UltiMaker2+ 3D printer, Thermoplastic Polyurethane filament with a Shore hardness of 95A (TPU 95A) and a finely knitted lycra (240 g/m2, 20% elastane) stretched up to 40% in the X and Y directions.

VERIFICATION THROUGH DESIGN EXPERIMENTS

Experiment 01

Experiment 01 examined the design of a crescent-shaped necklace with single curvature (positive only) geometry, which was developed using Method 01. A diamond-shaped pattern is applied to the bracelet model and adjusted to its Mean curvature analysis. The pattern density was increased in the flattest areas (blue) and decreased in the areas with the highest curvature (red). Experiment 01 includes three variations, whereby the pattern's density, stretch percentage (40%) of

Figure 4
Experiment 01 variants.

the fabric and textile type (lycra) remains the same, but the pattern's thickness is changing (Figure 4).

Variant V1.1 utilised a diamond pattern elongated in the y direction and a pattern thickness of 1.5 mm in diameter. Variant V1.2 utilised a diamond pattern elongated in the x direction and a pattern thickness of 1.6 mm in diameter. Variant V1.3 utilised a diamond pattern elongated in the x direction and a pattern thickness of 1.5 mm in diameter. All three variants were close to the original digital model, with variant V1.3 indicating the smallest displacement overall.

Experiment 02

Experiment 02 examined the design of a crescent-shaped necklace with a single curvature (positive only) geometry which was developed using Method 02. By applying the stress line simulation on the digital model, the stress line simulation pattern is generated as described in Figure 5. Experiment 02 includes three variations, whereby the pattern's density and thickness as well as the textiles stretch percentage were modified and adjusted, while the textile type (lycra) remains the same. Variant V2.1 utilised a dense stress line pattern with a pattern thickness of 1 mm in diameter and a stretch degree of 40%. Variant V2.2 utilised a less dense stress line pattern with a pattern thickness of 1.6 mm in diameter and a stretch degree of 40%. Variant V2.3 utilised a medium-dense stress line pattern with a pattern thickness of 1.5 mm in diameter and a stretch degree of 40%. Variant V2.4 utilised a medium-dense stress line pattern with a pattern thickness of 1.5 mm in diameter and a stretch degree of 30%. All four variants were close to the original digital model, with variants V2.3 and V2.4 indicating the smallest displacement overall.

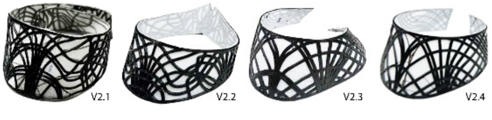

Figure 5
Experiment 02
variants.

Experiment 03

Experiment 03 examined the design of a crescent-shaped necklace with a single curvature (positive only) geometry which was developed using Method 03. By applying the form prediction algorithm to the digital model, the linear pattern is generated as described in Figure 6. Experiment 03 includes two variations, whereby the pattern's density and thickness as well as the textile's stretch percentage were modified and adjusted, while the textile type (lycra) remained the same. Variant V3.1 utilised a dense linear pattern with a pattern thickness of 3 mm in width and a stretch degree of 40%. Variant V3.2 utilised a less dense linear pattern with a pattern thickness of 6 mm in diameter and a stretch degree of 40%. Both variants were close to the original digital model, with variant V3.2 indicating the smallest displacement.

Figure 6
Experiment 03
variants.

FINDINGS

The findings regarding the performance of the different methods are presented in Table 1, a comparative displacement chart between variants and the digital 3D models used to design them. The outer dimensions of the artefact (length, width, height) are compared with the outer dimensions of the 3D model that was used to generate them. It becomes evident that variant V2.3 has the smallest discrepancies from the original digital model, followed by variant V3.2. All three of the tested methods proved to be performing to an acceptable level, however, Method 02, based on the stress line simulation appears to offer the most accurate reproduction of the original geometry. Variants V3.1 and V3.2 required the shortest 3d printing time (1.15 and 1.52 hours accordingly), while variant V1.3 required the longest time to print (2.35 hours). Furthermore, it becomes evident that variant V3.2, the most successful variant produced with method three was the heaviest (7.3 gr) thus, consuming the biggest amount of filament, while variant V2.3, the most successful variant produced by method two was much lighter (4.3 gr). This may be since the linear patterns of Method 03 are weaker and require more material to maintain the same shape compared to Method 02, whose patterns reminiscent of topology optimization provide a very efficient strength-to-weight ratio.

a higher displacement in the Y direction, while all variants produced with methods one and two have almost zero displacements in the Y direction.

How do the material properties of the individual components (the textiles and the fibres) contribute to the properties of the composite material? And how does the printed pattern geometry influence the form of the composite hybrid object? It appears that the relationship between textile type, rod thickness, stretching degree, pattern density and assembly method is very complex and particular, but

Variant	X/Y/Z Dimensions in mm	Stretching	Weight	Thickness	Printing Time
3D model	12.2/4.5/2.8	40%			
V1.1	5.5/4.6/3.2	40%	5.4 gr	1.5mm	2h30
V1.2	7/4.5/3	40%	6.2 gr	1.6mm	2h18
V1.3	7.2/4.5/3	40%	5.7 gr	1.5mm	2h35
V2.1	5/4.5/2.1	40%	5.2 gr	1.0mm	1h35
V2.2	6/4.5/2.2	40%	6.4 gr	1.6mm	2h24
V2.3	12/4.7/3	30%	4.3 gr	1.5mm	2h20
V2.4	8/4.6/3	40%	5.5 gr	1.5mm	2h15
V3.1	5/3.8/2.2	40%	4.8 gr	3mm	1h15
V3.2	13/3.5/2.6	40%	7.3 gr	6mm	1h52

Table 1
Dimensions chart of V1, V2 and V3 variants.

also essential for reproducing the desired objects. We could identify the following relationships: less dense patterns operate best when directly printed on the textiles, on thinner and more elastic fabrics, while a bigger rod thickness and width are required in order to reproduce the object effectively. Linear patterns perform best when the linearity follows the direction of the curvature, such as in variants V1.3, V3.1 and V3.2.

Finally, one could highlight the variety of forms that are made possible by combining these two materials into a composite object; the semi-elastic Thermoplastic Polyurethane 95 and the elastic fabric. Forms that apply to rules and material

CONCLUSIONS

Our conclusions focus on answering our research questions. Which of the three proposed methods assessed here is more effective in controlling and predicting the form and performance of hybrid panels composed of semi-flexible, pattern fibres printed onto flat elastic, pre-stretched textiles? Even though all three methods appear to be effective to a certain degree, methods 02 and 03 appear to be more efficient, in particular, as they managed to produce the most accurate objects. This becomes evident in Table 01 where the most accurately reproduced objects are variants v2.3 and v3.2. Method 1, based on the curvature analysis and penalization most successfully produced variant v1.3 whereby the direction of the diamond-shaped pattern (elongated in the Y-axis) influenced the object's performance. It is also notable that variants V3.1 and V3.2 composed of a linear pattern, showed

Figure 7
Completed
neckless variants

properties, as well as to pattern geometry and design (Figure 7). The success or failure of the final composite relies on the right proportion of design intentions and respect to the natural material memory and behaviour. This would allow us to enhance Frei Otto's call for lighter, more energy-saving, more mobile and more adaptable, in short, more natural buildings, or building components, such as roofs, ceilings, shading devices, tents, roofs and temporary shelters.

The limitations of this research project are linked to the size of all produced objects which is no bigger than 25 cm, which is the maximum printable size by the available 3D printers as well as a minimum rod thickness of 0.6 mm, linked to the minimum printable thickness by the printers. Our future plans include experimentation with larger-scale 3D printed objects, in order to verify our findings on a larger, architectural scale as well as examining the possibility of applying robotic technology for achieving more complex and reliable components.

REFERENCES

Agkathidis, A., Berdos, Y., Brown, A. (2019) Active membranes: 3D printing of elastic fibre patterns on pre-stretched textiles. International Journal of Architectural Computing 17(1):74-87. DOI:10.1177/1478077118800890

Agkathidis, A. and Varinlioglu, G., (2022). 4D Printing on Textiles: developing a file to fabrication framework for self-forming, composite wearables. In Advances in Product Design Engineering (pp. 61-81). Cham: Springer International Publishing.

Aldinger, A., Margariti A, Koerner, S., Suzuki, A. and Knippers, J. (2018) Tailoring Self-Formation: Fabrication and Simulation of Membrane-Actuated Stiffness Gradient Composites. In Creativity in Structural Design. Boston https://www.researchgate.net/publication/326552014_Tailoring_SelfFormation_fabrication_and_simulation_of_membraneactuated_stiffness_gradient_composites

Berdos, Y., Agkathidis, A., Brown, A., (2020) Architectural hybrid material composites: computationally enabled techniques to control form generation, Architectural Science Review, 63:2, 154-164, DOI: 10.1080/00038628.2019.1666357

Brown, A. and Rice, P. (2001) The engineer's contribution to contemporary architecture: Peter Rice. London, Thomas Telford

Cheng, T., Wood, D., Wang, X., Yuan, PF., Menges, A. (2020) Programming Material Intelligence: An Additive Fabrication Strategy for Self-shaping Biohybrid Components. In: Vouloutsi V, Mura A, Tauber F, Speck T, Prescott TJ, Verschure PFMJ (eds) Biomimetic and Biohybrid Systems. Living Machines. Lecture Notes in Computer Science, vol 12413. Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-64313-3_5

Cheng, T., Wood, D., Kiesewetter, L., Oezdemir, E., Antorveza, K., and Menges, A. (2021) Programming material compliance and actuation: hybrid additive fabrication of biocomposite structures for large-scale self-shaping. Bioinspiration & Biomimetics. DOI: 10.1088/1748-3190/ac10af

Erioli, A., and Naldoni, L. (2017) Informed flexible matter workshop. http://www. co-de-it.com/WordPress/informed-flexible-matter.html

Giglio, A., Paoletti, I., Conti, GM. (2021) Three-Dimensional Textiles in Architecture and Fashion Design: a Brief Overview of the Opportunities and Limits in Current Practice. Appl Compos Mater. https://doi.org/10.1007/s10443-021-09932-9

Goudswaard M, Abraham A, Goveia da Rocha B, Andersen K, Liang R, (2020) FabriClick: Interweaving Pushbuttons into Fabrics Using 3D Printing and Digital Embroidery. Proceedings of the 2020 ACM Designing Interactive Systems Conference. Association for Computing Machinery, New York, NY, USA, 379–393. https://doi.org/10.1145/3357236.3395569

Guberan, C., and Clopath, C., (2016) Active shoes. https://selfassemblylab.mit.edu/active-shoes. MIT Self-Assembly Lab

Joshi, S., Rawat, K., Karunakaran, C., Rajamohan, V., Mathew, AT., Koziol, K., Thakur, VK., Balan, ASS. (2020) 4D printing of materials for the future: Opportunities and challenges, Applied Materials Today, Volume 18. DOI: 10.1016/j.apmt.2019.100490

Jourdan, D., Romero, V., Vouga, E., Bousseau, A. and Skouras, M., (2022), October. Computational Design of Self-Actuated Surfaces by Printing Plastic Ribbons on Stretched Fabric. Computer Graphics Forum 41, 2, 493–506. DOI: 10.1111/cgf.14489

Jourdan, D., Skouras, M., Vouga, E., Bousseau, A., (2021). Printing-on-Fabric Meta-Material for Self-Shaping Architectural Models. In: Advances in Architectural Geometry, Paris, France. pp.1-19. ⟨hal-02925036⟩

Koch, HC., Schmelzeisen D, Gries T (2021) 4D Textiles Made by Additive Manufacturing on Pre-Stressed Textiles, An Overview. Actuators 2021, 10, 31. https://doi.org/10.3390/act10020031

Kycia, A. (2019) Hybrid textile structures as means of material-informed design strategy. In Ballestrem M, Borrego I, Fioretti D, Pasel R, and Weidinger J (Eds.), CA2RE Berlin Proceedings: Conference for Artistic and Architectural (Doctoral) Research, Berlin, pp. 34–35. Universitätsverlag der TU Berlin.

Meyer, P., Döpke, C., Ehrmann, A. (2019) Improving adhesion of three-dimensional printed objects on textile fabrics by polymer coating. Journal of Engineered Fibers and Fabrics. January 2019. doi:10.1177/1558925019895257

Otto, F., Rasch, B. and Schanz, S. (2006) Freí Otto, Bodo Rasch: Finding form: Towards an architecture of the minimal. Fellbach Axel Menges.

Redondo, FL, Giaroli, MC, Villar, MA de AGO, Ciolino, AE, Ninag, M D, (2020) Direct 3D Printing of Poly (lactic acid) on Cotton Fibers: Characterization of Materials and Study of Adhesion Properties of the Resulting Composites. Macromol.Symp, 394, DOI: 1900190. https://doi.org/10.1002/masy.201900190

Sitotaw, DB., Ahrendt, D., Kyosev, Y., Kabish AK . (2020) Additive Manufacturing and Textiles. *Applied Sciences*; 10(15) 5033. DOI: ttps://doi.org/10.3390/app10155033

Wu, JJ., Huang, LM., Zhao, Q., Xie, T. (2018) 4D Printing: History and Recent Progress. Chin, J. Polym Sci 36, 563–575. https://doi.org/10.1007/s10118-0182089-8-2089-8