2.5D: Novel Material Dimensions with 3D Printing on Fabric

by

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2.5D: Novel Material Dimensions with 3D Printing on Fabric

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ABSTRACT

Much of the design for architecture and objects we encounter today is built around the paradigms for manufacturing either two dimensional, flat goods, or three dimensional forms. We achieve an astounding proficiency in producing paper, fabric or sheet goods, whilst often encountering the familiar problem of logistics and assembly in creating anything in three dimensions. What if we were to combine the proficiency we have with the former, to produce volume, form, and structure?

2.5D is a proposal for a hybrid approach that applies 3D printing onto textiles and film material. The resultant method hopes to meld the design vocabularies of 2D and 3D design whilst presenting new possibilities with existing materials and technologies. Building on preceding research in 4.154 Interactive Intelligent Skins, this thesis takes the body as the most immediate context for architecture to present three objects as case studies.

The first is a reformable bag that suggests how fabric behavior might be modified with 3D printing. The second, a therapeutic garment that explores new materialities for variable flexibility and structure. And last, a shoe concept that addresses possibilities of mass customization and distributed manufacturing.

Responding to the challenges faced in the design of these, this thesis also puts forth a prototype design for a wide-format 3D printer capable of working with novel flexible filaments in the context of roll-to-roll textile and film manufacturing. When coupled with the techniques presented, this approach offers the tantalizing possibility to manufacture objects with complex structures and material behaviors, but in a manner that achieves accessibility with high volume output at relatively low costs.

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Title: Associate Professor of Design Research

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A big thank you too, to my fellow thesis students and studiomates for their camaraderie. Particular thnks Daisy for helping with the documentation of the work

For their unrelenting support and enthusiasm for my work, I also owe all my gratitude to Bella, alongside TImmy and Sally.

Lastly, this thesis would not have been possible without the broader open-source community and the wealth of knowledge they have so generously shared.

Introduction

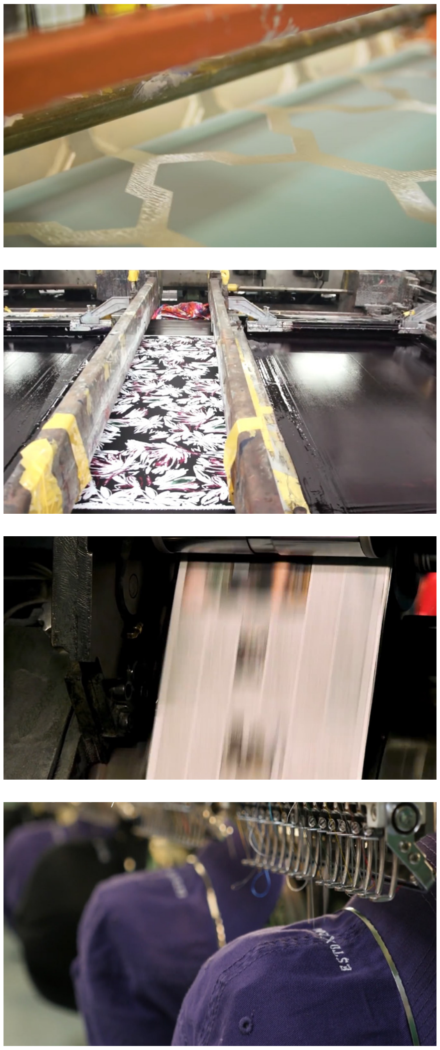
More than 2, less than 3

This thesis is so named for two strands of design research that it engages with. The first is for defining a domain of design that operates between a surface and the volume or form that it engages with. The second, for an ambition to combine the throughput of two-dimensional manufacturing processes, with additive manufacturing, so as to contribute to a new paradigm of how we design and make things.

Much of the foundational work for this thesis began in the realm of fashion with 4.154 Interactive Intelligent Skins, taught by Associate Professor Skylar Tibbits, in collaboration with fashion designer and CAST visiting artist Hussein Chalayan. At the scale of this most personal of architectures, we were tasked with exploring material and fabrication technologies in pursuit of a second "skin", one capable of actuation and interaction, but also embodying creative expression.[1]

One of my greatest takeaways from that semester was getting acquainted with the design and prototyping process that many fashion designers engage with. In a blend of intuition, experience, and skill, these designers work primarily with two-dimensional patterns to translate otherwise flat materials into form, volume, and structure. It is this space of design that this thesis engages with, introducing an additional material dimension by applying available technologies of 3D printing to fuse filament directly onto film or fabric.

In a more literal reading of "2.5D", this thesis also signals an ambition to rethink how we design and produce three dimensional products. In this day and age, we are expedient at manufacturing two-dimensional, textile, and sheet goods. From inkjet and offset printing, to embossing and lamination, we have developed an entire repertoire of technologies to apply to various flat media, and we do so not just with paper or textiles, but with more architectural materials, such as plasterboard, vinyl, tile, and plywood.



Two-dimensional industrial processes.

From Top: Roll printing, screenprinting, offset printing, and embroidery

As such, many of the paradigms for manufacturing objects or buildings revolve around translating this sheet material into some shape or structure. This leverages the fact that sheet material is easier to store, handle, and transport, but also functions to navigate around more complex three dimensional processes. Stamped sheet metal is a good example of this; a process designed to avoid more conventional methods of metalworking to more efficiently work with sheet metal, but with some tradeoffs of geometry and material properties. In a similar manner, 2.5D proposes to bridge the throughput of two-dimensional processes and the need for complex three-dimensional objects.

Much of the work of this thesis has been about experimenting with the technique of printing on fabrics to understand what it is capable of, and to design to those potentials. The result is three case studies of a bag, a garment and a shoe. They illustrate, respectively, a potential for modifying fabric behavior, a new material gradient of flexibility, and an innovative approach to the custom design and in-place fabrication of an object that inherently requires volume and structure.

In pursuit of this ambition, and in response to some of the design challenges faced with the case studies, this thesis also puts forth a design for a roll-to-roll 3D printer. This printer is designed to work with standard widths of roll fabrics and film, with the potential for automating the fabric movement as part of the printing process. Whilst the design presented is a prototype, I believe it is sufficient in demonstrating how it might work more efficiently with roll fabrics and film, as well as allow for the design of objects at larger scales.

This thesis is organized as follows: Chapters 1 and 2 will delve into the specifics of the materials and technologies that enable this design research. Chapters 3 through 5 will present the aforementioned case studies and particular aspects of the potential of 2.5D. Chapter 6 will document the process and design of the roll-to-roll 3D printer. The final chapter looks toward the future of this work and outlines some of the potential avenues that it might explore.

1. Skylar Tibbits, “Architecture Design Option Studio: Interactive Intelligent Skin (Tibbits) | MIT Architecture,” accessed May 18, 2022, https://architecture.mit.edu/subject/fall-2021-4154-4s01.

Chapter 1

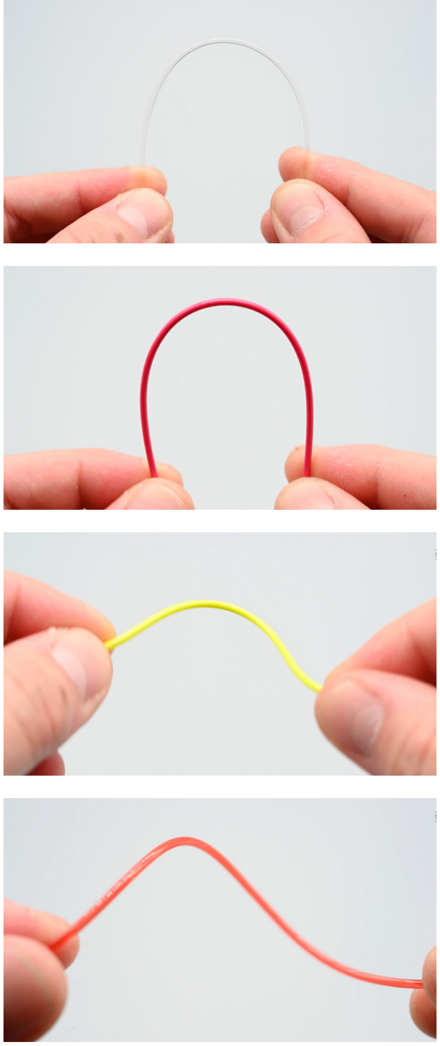
Materials

As mentioned in the introduction, this thesis primarily employs the technique of applying additive manufacturing, or 3D printing as it is commonly known, directly onto films and fabrics. The specific additive manufacturing technology used is fused filament fabrication (FFF), also known as fused deposition modeling (FDM). Simply put, this is the controlled deposition of a heated thermoplastic that is then cooled and solidified, typically forming an object through successive layers. In modifying this process, this thesis has predominantly used thermoplastic polyurethane (TPU) in both its film and filament form; mounting it as a substrate on the print bed and fusing filament directly onto it.

TPU: Filament and Film

Thermoplastic polyurethane, or TPU as it is commonly referred to, is a type of thermoplastic elastomer. The term polyurethane is actually a description for a class of polymers rather than a definition for a specific chemical.[2] [3] They can be formed by a variety of monomers and additives, and simply share the characteristic of being joined by urethane groups. The modifier "thermoplastic" is actually an important distinction, as polyurethane, or PU, is typically a thermoset plastic, meaning that any thermal deformation it experiences is irreversible. As can be inferred, thermoplastics can, instead, experience repeatable thermal deformation, becoming more plastic with heat, and solidifying when cooled.

Thermoplastic elastomers are a relatively new category of plastics that exhibit viscoelasticity, i.e. changes in viscosity and elasticity when they undergo deformation. The material has seen extensive research for biological and medical use, such as with microfluidics and nano-structures, but may



Previous Page: Close-up of TPU

This Page, from Top: Various types of TPU filament with different Shore Hardness also be more recognizable to the layman in inflatables and the latest sports shoes. Whilst this thesis will not delve into the chemical makeup of specific types of TPU, it will engage with the range of material properties that they offer.

Two material properties of TPU, in particular, allow for this thesis' modified FFF method to work. First, the thermoplastic exhibits a lower complex viscosity than other thermoplastics at their suitable temperatures for FFF.[4] Essentially, this means that TPU is able to flow better on the print base or substrate that it is printed on. In conjunction with this behavior, TPU also exhibits a high level of adhesion once it re-solidifies, comparable to that of the commercially available polyurethane adhesive, Loctite.[5] With the TPU substrate, this adhesion is also aided by how the film thermally deforms around the heated print nozzle and along with freshly extruded filament.

One of the key variables of TPU utilized in this thesis is its hardness. This is typically measured on the Shore Hardness Scale, with overlapping scales of Shore 00, Shore A and Shore D that offer different points of reference for various materials.[6] [7] This thesis has primarily experimented with TPU within the range of 75D - comparable to nylon or a hard rubber - down to a 60A, which is akin to a soft silicone. Whilst a number of different filaments were evaluated, the following list encapsulates the range explored:

- SainSmart All Colors TPU (92A and 95A)
- NovaMaker TPU (95A)
- Overture Flexible TPU (95A)
- Overture High Speed TPU (95A)
- Ninjatek Armadillo (75D)

These filaments provided a palette of colors and transparencies to work with, along with varying levels of hardness and flexibility. Even amongst the filaments rated for the same Shore Hardness, however, they exhibit differences in the printing process, having been calibrated for different temperatures and flow rates. Typically, however, most TPU is printed in the range of 210°C to 250°C, and require no heated bed, or a low heated bed temperature between 30 - 60°C.[8]

Compared to the filaments, the properties of the TPU film used as a substrate have been more opaque. From testing a

2. Nomenclature for thermoplastics is typically informed by the source monomer for the plastic. Poly-, meaning many, followed by the monomer used. Eg. Polystyrene, polyethylene. The naming of TPU, or PU, differs from this slightly.

3. Azo Materials, "Understanding Plastics and Polymers - The Different Types of Plastic," AZoM.com, January 20, 2019, https://www.azom.com/article.aspx?ArticleID=17477.

4. Conor G. Harris et al., "Additive Manufacturing With Soft TPU – Adhesion Strength in Multimaterial Flexible Joints," Frontiers in Mechanical Engineering 5 (2019), https://www.frontiersin.org/article/10.3389/fmech.2019.00037.

5. Harris et al.

6. Sagar Habib, "What Is Shore Hardness Scale? | The Complete Guide," PlasticRanger (blog), August 25, 2021, https://plasticranger.com/what-is-shore-hardness-scale/.

7. Note that hardness and elasticity, whilst measured differently, are also related. A Shore Hardness value for a material can be converted to a Young's Modulus, and vice versa.

range of samples, and in dialogue with retailers and distributors, I gathered that the additives used to color and opacify TPU film have an impact on its elasticity and melting point range. With this thesis, I experimented with multiple TPU film types and settled on a translucent 0.2mm film for its availability and workability.

This general specification of material worked well with the fabrication process for a number of practical and technical reasons. First, the matte translucent film, in contrast to the glossier films, had less of a tendency to stick to itself. Partially related to this, they also tended to stretch more evenly, allowing it to be more easily prepared and secured to the print bed. In finding an appropriate thickness of film, TPU of various thicknesses from 0.05mm to 1mm were initially experimented with. I quickly found that the thinner film tended to exhibit too much variance in thickness to reliably accommodate the tolerance and vertical offsets of the printing process, and thicker material just tended to be exponentially costlier. I would have continued to experiment with various types of film and from different sources, save for the difficulties introduced by persistent supply chain issues in the years 2021 to 2022. It was simply easier and more economical to persist with the 0.2mm film.

8. Jackson O'Connell, "The Best TPU Bed & Print Temperature Settings," All3DP, May 15, 2022, https://all3dp.com/2/best-tpu-print-temperature-bed-filament/.

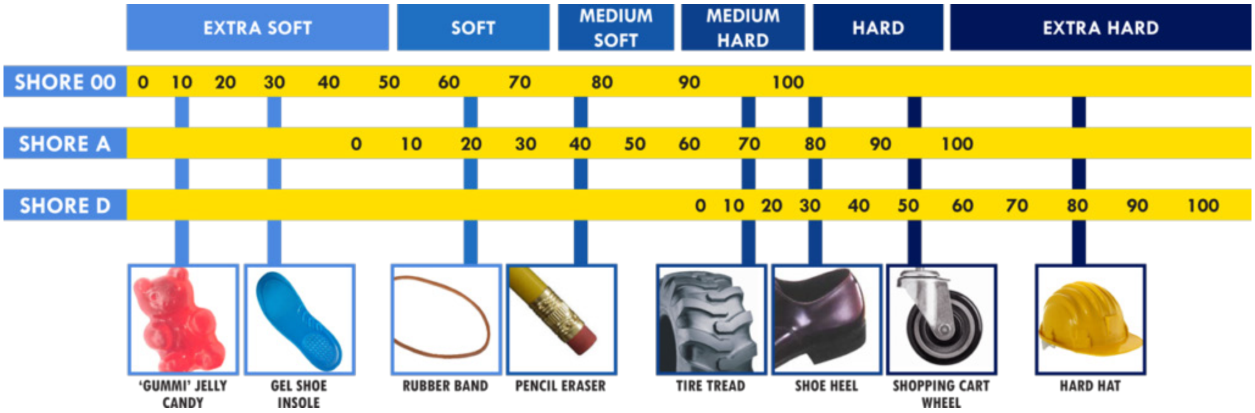


Illustration of Shore Hardness range with reference objects

Mono-material Design and Environmental Considerations

Before proceeding with the specifics of how TPU was used in this thesis, it is perhaps worth taking a moment to highlight a part of my motivation for working with this material in both its filament and film forms. Whilst initially chosen for its role as a more environmentally-friendly alternative to polyvinyl-chloride (PVC), its environmental benefits extend far beyond that.

One of the latent promises of additive manufacturing is efficiency, not only in the distribution of material to where it is needed, but also in how the material is used in the manufacturing process. When the 3D-printed object is no longer needed, there is the additional potential of recycling it back into filament.[9] Broadly speaking, this notion of a circular economy for plastics is made more possible with mono-material objects, 3D-printed or not. Whilst not a focus of research in this thesis, it is sufficient to state that most of the designs presented do classify as mono-material.

Objects are not made more recyclable, however, just by virtue of being mono-material. Many thermoset elastomers, for example, are homogenous and mono-material, but feature cross-linked chemical structures that make them difficult to recycle.[10] TPU, however, achieves its elastomeric properties with "pseudo cross-links"[11], which disappear as the material is melted, but reappear when cooled. This allows for the material to be more easily reprocessed with heat, or with a chemical solvent. Research has even shown that any degradation in the material properties of recycled TPU is asymptotic, making it easier to predict and work with.[12]

Outside of the circular economy of the material, there are also important ecological advancements with TPU at the start and end of its life cycle. New formulations of the material can allegedly source up to 70% of its carbon from biomass, thereby greatly reducing the environmental impact of its production.[13] And at the other end of its material use, certain TPUs can even be designed to be completely biodegradable in the right conditions.[14]

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9. David Roberson, "3D Printing and the Circular Economy," https://ultimaker.com, November 5, 2021, https://ultimaker.com/learn/3d-printing-and-the-circular-economy.

10. Ali Fazli and Denis Rodrigue, "Waste Rubber Recycling: A Review on the Evolution and Properties of Thermoplastic Elastomers," Materials 13, no. 3 (February 8, 2020): 782, https://doi.org/10.3390/ma13030782.

11. Gity Mir Mohamad Sadeghi and Mahsa Sayaf, "From PET Waste to Novel Polyurethanes," in Material Recycling - Trends and Perspectives (IntechOpen, 2012), 357–90, https://doi.org/10.5772/31642.

12. Bastian Wölfel et al., "Recycling and Reprocessing of Thermoplastic Polyurethane Materials towards Nonwoven Processing," Polymers 12, no. 9 (September 2020): 1917, https://doi.org/10.3390/polym12091917.

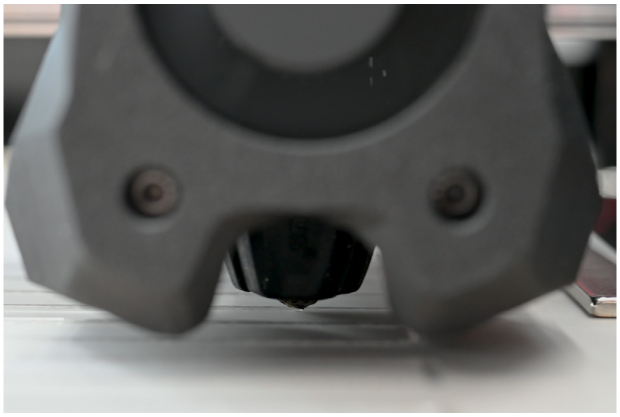
13. Lubrizol, "Bio TPUTM - Lubrizol," Lubrizol, accessed May 18, 2022, https://www.lubrizol.com/Engineered-Polymers/Technologies/Bio-TPU.

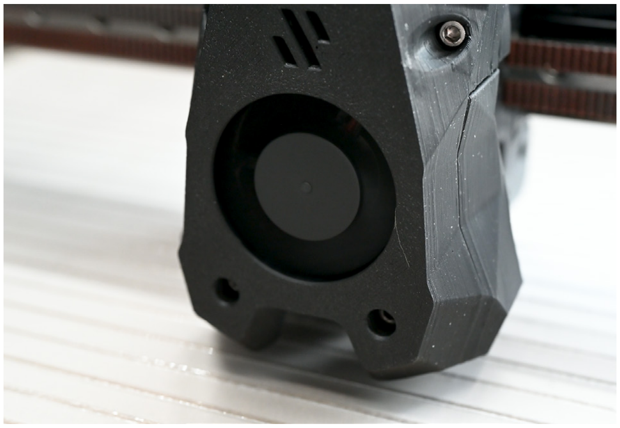
14. Zhaoshan Wang et al., "Fabrication and Properties of a Bio-Based Biodegradable Thermoplastic Polyurethane Elastomer," Polymers 11, no. 121 (2019), https://www.mdpi.com/2073-4360/11/7/1121/pdf.

Next Page: Video Stills of Fabrication Process


CAUTION: HOT STEAM


28
30
31
32





Chapter 2

Methods

Methodology

With the material properties of TPU described above, the fundamental process of 3D printing on the TPU film is surprisingly straightforward. While the specifics are recorded later in this chapter, most of the work of this thesis was done with a typical kit 3D printer and a hobbyist open-source design that I assembled. In both cases, the film or fabric substrate was secured to the magnetic build plate with thin neodymium magnets, or alternatively, with binder clips. An appropriate offset was also applied to the Z-axis of the print according to the thickness and material of the substrate.

Perhaps the most laborious part of the process was in ensuring that the fabric or film was sufficiently flat and taut on the build plate. With the tolerances of 3D printing typically on the order of 0.1mm, it is important to minimize the amount of slack in the fabric. Too much, and the fabric could start to bunch up around the nozzle, possibly melting with prolonged contact, or simply impede the print process. My approach to this involved first steaming or ironing the fabric to remove any creases, and then systematically attaching it to the build plate with clips or magnets in a way that applied even tension across the material. I also rarely used a heated bed with the prints to avoid any uneven expansion of the substrate material.

The adhesion of extruded TPU filament onto the TPU film was rarely an issue, even across different sources of material and colors of film. Some experimentation with the temperature and speed of the first layer of the print usually resolved any adhesion issues. The adhesion of TPU filament was found to be so reliable that I experimented with printing it on TPU-coated fabrics as well as more porous, non-TPU fabrics. That said, the printing of TPU filament on TPU film was arguably the most repeatable.

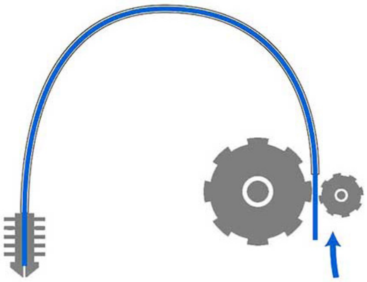


Diagram of Bowden Setup

Challenges, Discoveries, Solutions

The challenges of using TPU filament with FFF may be largely associated with three common printing parameters: speed, temperature, and flow.

Speed

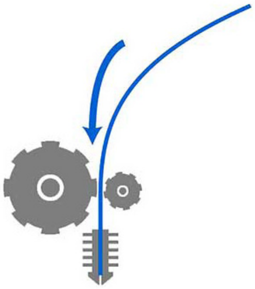
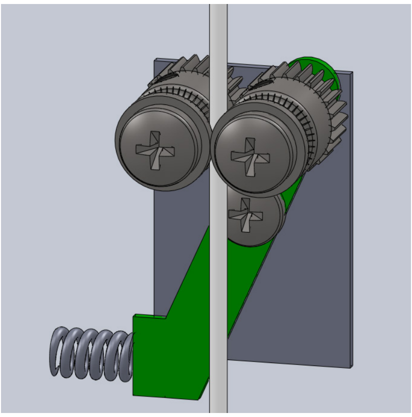


Diagram of Direct Extruder Setup


3D Model view of a dual-drive extruder

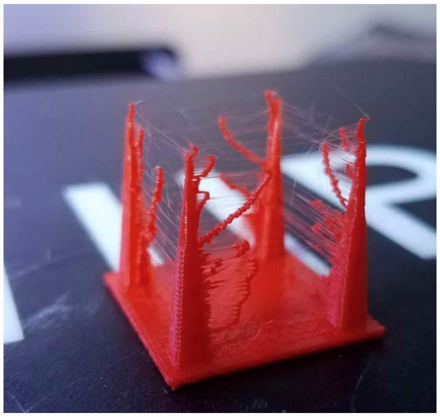
Whilst the very elasticity of TPU enables the designs later presented in this thesis, it also poses a significant challenge to its workability and the speed at which it is printed. The play in the length of filament as it moves towards the printer's hotend can cause issues with the mechanics of the chosen printer. Move the TPU filament too fast - or too suddenly -, and the material can slip between the gears of the motor that is pushing or extruding the filament. Any significant gaps along the filament's path towards the hotend can also cause the material to slip out of place, or obstruct incoming material. As such, typical advice for printing with TPU often begins with slowing down the print speeds. Compared to more commonplace thermoplastics used in 3D printing, such as PLA or PETG, this can mean a three- to five-fold speed reduction

Design choices in the mechanics of the 3D printer used can alleviate some of these issues. For example, Direct Drive setups, with a fully supported filament path, are often recommended. A dual drive extruder motor with adjustable tensioning also helps to prevent the filament from tangling. With this, two drive gears are linked to move in tandem to apply an even pressure on the filament when advancing or retracting it. When working with a simpler direct drive extruder assembly that utilizes an idler gear, however, I have also found that simply reducing the tension applied to the filament, in tandem with a moderate decrease in print speeds, also allows for reliable printing.

Temperature

To compensate for reduced print speeds, one might then be tempted to increase the temperature of the print, or use hotends with higher volumetric capacities. After all, a hotter extruder would allow for the filament to be pushed through more freely. Due to the low complex viscosity of TPU, however, it should come as no surprise that the material “oozes” a lot. In other words, it leaks out of the nozzle regardless of whether the extruder motor is advancing the filament - a phenomenon only exacerbated by higher temperatures.

A typical solution to this with other thermoplastics might be to introduce a retraction, where the extruder motor is set to intentionally pull back the filament by a short distance at the end of every length of extrusion. However, as discussed above, with TPU’s elasticity, excessive and rapid retraction can also cause the material to slip around the extruder gears, or simply not move back in place when needed.



Example of stringing phenomenon

Flow

In balancing the speed and temperature of the print, we logically come to the issue of print flow. Essentially, this refers to the rate at which the filament is extruded out of the nozzle. In working with the material, I have found that keeping this as consistent as possible, with gradual accelerations and decelerations, makes for the most consistent prints. Most of this can be specified either at the machine level with software limits, or within slicing software with sufficiently detailed controls.

With regards to slicing software, some attention should also be paid to the use of certain common features. Extra dense layers, where the nozzle’s toolpath is made to overlap significantly, should be closely monitored. This is typically inserted by the software to generate internal bridges, fill small gaps, or to create a seamless appearance on external surfaces. In these scenarios, if the nozzle is consistently in close contact with already printed filament, the flow of freshly extruded TPU can be impeded. This then creates a back pressure up the filament path, often causing the problems discussed above, such as clogging in the hotend, or even tangling of the filament in the extruder gears.

One of the ways to ensure a more consistent filament flow is with a larger than average nozzle diameter. Here, there is some tradeoff, as smaller nozzles typically allow for finer detail and smaller layer heights, but consequently also increase the back pressure applied up the filament path. Too large a nozzle, however, and you also tend to aggravate any issue of "oozing" as discussed above. In my testing, I found that a 0.6mm nozzle was a good balance between detail and workability. Specially designed high-volume nozzles, as well as limits on linear and volumetric printing speeds can also aid in mitigating this issue.

To recapitulate, the elasticity of TPU that this project leverages also significantly impacts its workability, and mitigating this requires the careful management of speed, temperature, and flow in the FFF process. That said, I offer three methods to print TPU more rapidly and reliably. The first and possibly easiest option is to choose TPU filament that has specially been designed to be easier to print. The Overture "High Speed TPU" is an example of this, being noticeably stiffer than other TPU rated at Shore 95A, but retaining a similar hardness after being printed.

Second, one might simply select a more appropriate hotend and heating element. Though certainly not the only example of this, the Phaetus Rapido[15] used in the Voron printer setup of this research is a good example of such a hotend design. With even heating via a ring-shaped, ceramic cartridge, and a well-designed heartbreak, the hotend achieves a significant volumetric output that has been experimentally tested and verified.

The last method is markedly more involved. With some print management firmware, an option often referred to as "pressure advance" is available. As the name suggests, this variable enables the software to manage the acceleration of the advancing filament in a way that controls the pressure applied on the print nozzle. As alluded to earlier, balancing this pressure with the temperature of extrusion can result in faster print speeds. Anecdotally, speeds of up to 400mm/s have even been achieved in the open-source community.[16] [17]

I will save further discussion of the possible technologies that might address the rapid printing of TPU for later. Suffice to say, the fabrication setups used in this thesis were tuned to reliable print TPU at speeds of 60mm/s to 100mm/s with a 0.6mm diameter nozzle, already close to the theoretical volumetric limit of the hotend used.

15. Phaetus, "Rapido Hotend – Phaetus," Phaetus, accessed May 18, 2022, https://www.phaetus.com/rapido-hotend/.

16. Johan Eriksson, Voron 2.4 LGX TPU 400MM/s, 2021, https://www.youtube.com/watch?v=Suj1oOBWXQw.

17. Vez3D, Nova Hotend TPU Speed Test 400mm/s?, 2021, https://www.youtube.com/watch?v=4YoOWPem0YU.

Geometry

In addition to the more technical solutions adopted, I also began to address the challenges of printing TPU through design and geometry. Whilst I will delve into more detail about these geometries with the case studies, allow me to highlight two of them that are pertinent to the material characteristics of TPU that we have discussed.

In dealing with of oozing or stringing,[18] for example, I began by managing the travel paths of the print head within the slicer, but also eventually developed a system of line-based geometries to work around the issue. Essentially, these geometries were designed in close relation to the chosen nozzle diameter in a manner that maximized continuous, single-line toolpaths. Simply put, if the hotend is moving and printing continuously, there is less opportunity for errant TPU to leak. This approach is most notable in the detail and tool pathing of the “flex zip” that is used in all three case studies.

The low complex viscosity of TPU also means that it is not particularly adept at bridging. In the process of FFF, bridging is where extruded filament is rapidly extruded, and then cooled and solidified to allow material to span between two distant points of support. Particularly with softer TPUs, it is hard to achieve this at meaningful lengths. The bump-based geometry of the second case study was designed to account for this limitation. Similar to how a corbeled arch might be approached, the walls of the enclosed volume adhere to an acceptable overhang angle until the span between opposite sides of the volume is sufficiently small.

Whilst perhaps seemingly obtuse in the abstract, the material characteristics of TPU have deep implications for geometrical choices in designs, and have provided context for my development of various details and geometries in the case studies.

Next Page:

A series of material and geometry experiments exhibiting

1) different hardnesses of TPU filament and geometries

2) Ability to seal air within a volume of printed material

3) Example of Flex Zip detail actuating adjacent geometry

4) Bump-like geometry being actuated

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[18] Brian Obudho, “3D Print Stringing: 5 Easy Ways to Prevent It,” All3DP, January 6, 2022, https://all3dp.com/2/3d-print-stringing-easy-ways-to-prevent-it/.

Outline of Design and Fabrication Process

In concluding this chapter, I offer an outline that situates the above discussion of materials and methods within the process I undertook with this thesis

1) Conceptualizing a design and selecting a TPU with appropriate shore hardness and appearance.

2) Calibrating a print profile for the chosen filament that considers:

    a) the lowest viable print temperature
    b) optimal speed and acceleration
    c) consistent print flow
    d) an overhang angle limit or bridging span limit

3) Refining the concept design with appropriate geometries and filament-specific constraints.

4) Translating the geometries to G-code with a slicer, with special attention towards:

    a) minimizing dense layer geometries
    b) optimizing seam points
    c) maximizing single-line toolpaths

5) In preparing for the print, the fabric or film used as the substrate is then steamed or ironed.

6) The substrate is then secured to the print bed with even tension, using magnets or binder clips.

7) Print!

Minimal post-processing was done on most of the prints in this thesis, usually only involving the removal of some "stringing" artifacts. I have found that even these, however, can be effectively minimized with an appropriate slicing profile, judicious use of geometry, and some of the considerations previously discussed.

Dimethyl sulfoxide, or DMSO, was briefly experimented with as a solvent to polish the TPU prints and remove the visible lines between deposited layers of filament. The chemical is a common by-product of paper production and a medical ingredient.[19] It was found to be effective as a pos-

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[19] American Chemical Society, "Dimethyl Sulfoxide," American Chemical Society, accessed May 18, 2022, https://www.acs.org/content/acs/en/molecule-of-the-week/archive/d/dimethyl-sulfoxide.html.

sible means for this kind of post-processing, but a manual application of it was simply not well controlled enough.

Instead, a process known as vapor smoothing might be more appropriate in executing this.[20] Typically done with ABS or PLA, this involves placing the printed part above a shallow amount of the solvent and enclosing the two. This allows for the solvent to evaporate and yet remain in proximity to the print, gradually and evenly working on the exterior surface of it.

In Chapters Three through Five, I will present a series of case studies and objects that highlight certain aspects of the 2.5D process. Each chapter will generally describe the motivation behind the designs and the fabrication process, but also take a more in-depth look at particular details and geometries that were developed.

Effects of vapor smoothing of ABS

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[20] Lucas Carolo, "ABS Acetone Smoothing: 3D Print Vapor Smoothing Guide," All3DP, April 25, 2022, https://all3dp.com/2/abs-acetone-smoothing-3d-print-vapor-smoothing/.

Chapter 3

Modifying Fabric

One of the most immediate benefits of 3D printing on fabrics is the material synergy that it creates. With regards to 3D printing, this process allows for designs that can overcome some of the typical constraints of the technology. These designs are less restricted by the dimensions of the printer bed or volume, and by way of the fabric, also achieve a flexibility and continuity not typically found with 3D-printed objects. Conversely, 2.5D also affords the exciting potential to modify the material behaviors of the fabrics beyond what is conventionally possible.

Through careful design of the type of printed filament used and the geometries they are made to form, we are able to alter the appearance of fabric, modulate its flexibility, and even introduce new ways to structure and attach it. Perhaps the most promising attribute of this is that additive methods also allow for a possible gradient of these behaviors. Imagine a piece of fabric that is silky, soft, and translucent at one end, but gradually made to turn rubbery, hard and opaque towards the other. This idea of a functionally graded material is not new, and, in the context of additive manufacturing, can perhaps best be attributed to the work of Neri Oxman[21] and Alexandros Tsamis.[22] This aspect of the technique, however, does add to the inherent allure of a continuous surface of fabric.

Video Stills of process of activating clasps, reforming tote bag

Previous Page: Reformable Bag design

Reformable Bag

Descending from such giddying promises, this first case study invites the reader to consider something much more quotidian: the tote bag. The inspiration for this series of designs began with the rather whimsical notion of being able to carry coffee cups or fragile objects in my favorite type of bag, but without the coffee spilling, or the objects constantly knocking into each other. In a nod to the growing ubiquity of the home 3D printer, these designs also started with the constraints of the more commonplace printer I had access to, the Prusa.

The first of these bags features a rather straightforward and simple method of modifying the fabric of a normal tote bag. On the outer face of the material, two pairs of orange clasps were printed with a sturdier TPU. These are easily manipulated by hand, allowing the bag's user to squeeze them in order to hold in place two cups. Due to the thermoplastic nature of the material, applying a clothes iron or hair dryer to these clasps easily resets their geometry.

On the inside of the bag, a more flexible TPU was used to create a series of what I will refer to as "flex zips". These serve to create pockets as well as internal dividers to separate objects in the bag. These zips behave similarly to that on resealable zipper storage bags, and squeezing opposite sides of the zip between your fingers provides enough pressure to attach the "teeth" and secure them in place. I might add that there is a certain tactile pleasure in connecting these zips, but I can only leave that to the reader to experience in person!

This dual-sided design was produced on the Prusa printer with no modifications, but with some basic considerations for the setup. As the external clasps were first printed, followed by the fabric turned over for the interior zips, the design had to consider both sides of the bag simultaneously. Not only could the printed parts not overlap, but they also had to provide enough clearance for securing the fabric, and for the print head assembly as it moved about the toolpaths.

Subsequent iterations of the tote bag engaged more with the design of the harder TPU on the outside of the bag. Playing off the appearance of a drawing of a bag, a scattered point geometry was formed around a scaffold of lines. This provides a similar function to the clasps of the first bag, but, in the spirit of 3D printing, can also be randomized to provide multiple visual iterations of the same basic design.

Functionally, the more extensive exterior design also enables new material interactions. The web-like structure of harder TPU may be deformed, either by hand or with the assistance of heat, so as to reshape the bag. Like the clasps, this can also be reset with the application of mild heat. Ad-

Video stills showing integrated flex zips and the process for securing them

21. N Oxman, Steven Keating, and E Tsai, "Functionally Graded Rapid Prototyping," 2011, 483–89, https://doi.org/10.1201/b11341-78.

22. Alexandros Tsamis, "Digital Graft : Towards a Non-Homogeneous Materiality" (Thesis, Massachusetts Institute of Technology, 2004), https://dspace.mit.edu/handle/1721.1/28810.

ditionally, the rigidity of the exterior print can also be used to create a vertical, internal divider, by pulling the bottom of the bag up into itself. With the thin TPU structure bending against itself, the divided compartments are semi-rigid and can hold fairly heavy objects.

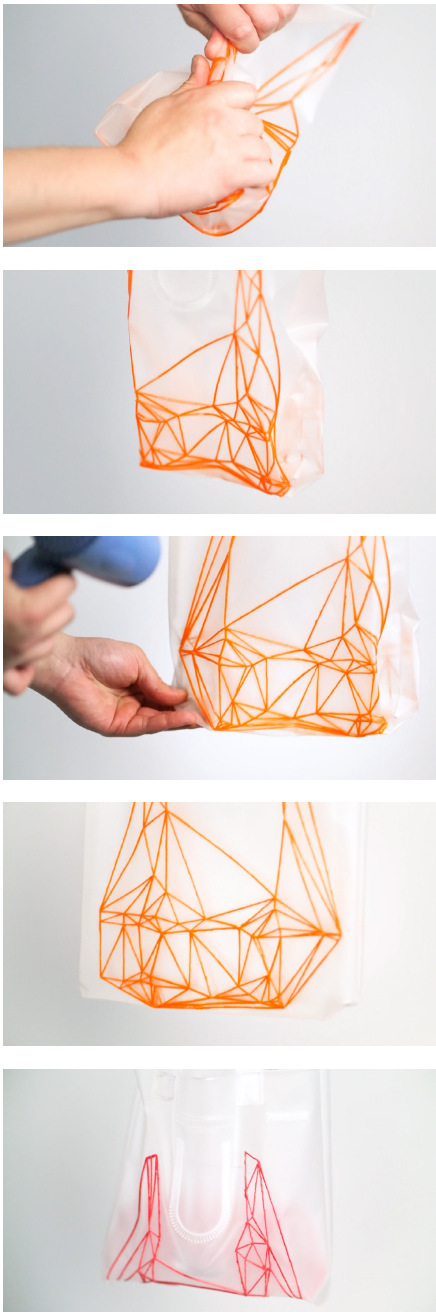
With a total print time of under two hours, the tote bag designs are a good illustration of how even a minimal amount of 3D printing can significantly modify the behavior of fabrics and allow for new material behaviors and interactions in even the most everyday of items.

Detail - Flex Zip

As it is a recurring detail with the subsequent case studies, it is perhaps appropriate to elaborate on my design of the flex zip. Typically printed in a softer TPU in the range of Shore 92A to 95A, the flex zip relies not just on the friction between the zip's teeth, but on the relative elasticity of the printed geometry and the stretch of the fabric or film it is printed on. As such, it is able to function not just in linear arrays, but in controlled, curved shapes as well.

The perpendicular "spine" on the outer edges of the zip serves to provide some rigidity to the fastener, but was actually first conceived as a way to mitigate oozing and stringing, and to minimize post-processing with the prints. Imagine, if you will, the nozzle having to print an array of rectangles, but with the oozing of the TPU, leaving blobs and strings of the material as it jumps from shape to shape. With the dimensions of the "spine" and zip teeth calibrated to the chosen diameter of the print nozzle, this geometry instead allows the printhead to move in a single, continuous line for each layer, with minimal filament retraction and travel moves.

The spacing of the zip teeth is determined not just with the chosen diameter of the print nozzle, but in a process of experimentation for each type of filament and the substrate it is printed on. For example, a flex zip printed with the same filament at a particular spacing may work well on one type of TPU film, but be too loose to be functional on a more elastic film. With adjustments to the geometry often occurring within the range of 0.05 to 0.1mm, it was important for me to thoroughly understand the technical undertaking of translating designed geometry into printed geometry.



Video stills showing how the harder TPU can be reformed by hand or with heat to take on new shapes

Bottom image is of a reformable bag with its internal divider activated

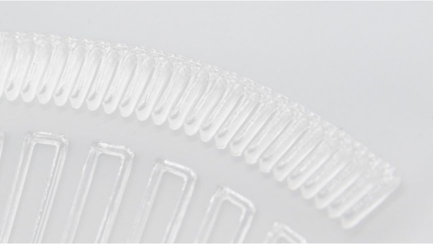
Between the flex zip model and its sliced counterpart, we might observe some key geometric changes. First, owing to the kinematic limitations of any 3D printer, the vertical edges of the model are just slightly rounded out by the slicing software. More consequently, however, is that the width of each layer of the slice might be different from what was designed with the original model.

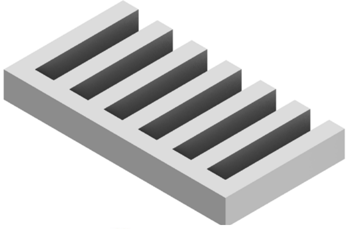
This discrepancy is sometimes driven by the diameter of the nozzle specified in the slicing software, but also by the variable of extrusion widths and flows in the print settings. For example, the external perimeter of a printed layer is very commonly specified to 140% width, meaning that the printer attempts to force a wider than normal line to be extruded. This is typically done to aid with adhesion along the outer surface of a print, but in the case of a flex zip, would provide an inaccurate and non-functional print. At the risk of sounding pedantic, all this is to highlight the role of the slicing software as an often, unintended translator of geometry and design. Any designer wanting to critically approach 3D printing should certainly pay attention to its impact on function and aesthetic.

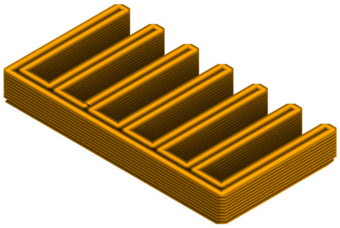
I believe the flex zip is one of the most potent details I have developed in this thesis, offering a satisfying tactile interaction, and a range of applications and functions. In the process of the thesis, I have explored some variations on the design, including curved zips, longer, clip-like zips, as well as sliding and directional zips. That said, with the case studies, the use of the flex zip can be broadly divided into two categories.

First, the zip allows for directional fastening in the designs. In the collar configuration of therapeutic garment in the second case study, a sliding zip at both ends of the pattern function not only as an edge detail, but as a way to adjust the fit of the garment in a continuous manner. This is much like the gradient of tightness allowed by drawstring pants, as opposed to a typical belt. In the third case study, the zips not only allow for the configuration of the shoe, but also for tension to be held in different directions in its material.

Second, the flex zips serve to help guide and predict the behavior of the reconfigurable geometries. With the therapeutic hood in particular, the shape and orientation of the zips, in relation to the other printed geometries, were used to predetermine what kind of flexibility the design could adopt when the zips were fastened.







From Top:

Detail of Flex Zip

Video still of flex zip pocket being activated

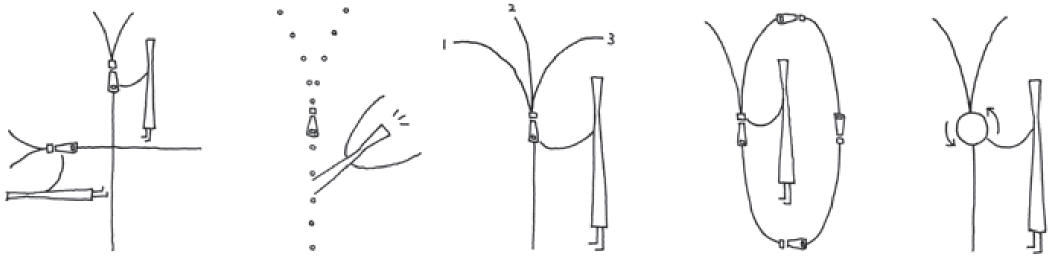
Rendering of original modeled geometry for a flex zip

Sliced geometry of the same flex zip

Much like the project nendo developed for YKK,[23] future development of the flex zip should further break the mold of what we can expect from these fasteners. I could imagine different permutations of the zip that interact with other more complex printed geometries to produce a wider expression of material interactions.

These zips could also provide new ways to connect and fasten different types of sheet material, and perhaps even to surfaces we do not associate with zips at all. Putting technological constraints aside for a moment, what might the zip start to look like if we were to use it to attach fabric to a metal sheet? A board of wood? A cylindrical, concrete column? A rock?

The potential for this detail far exceeds what it has been specified to do with these case studies.



Sketches by nendo illustrating five concepts for novel zip designs

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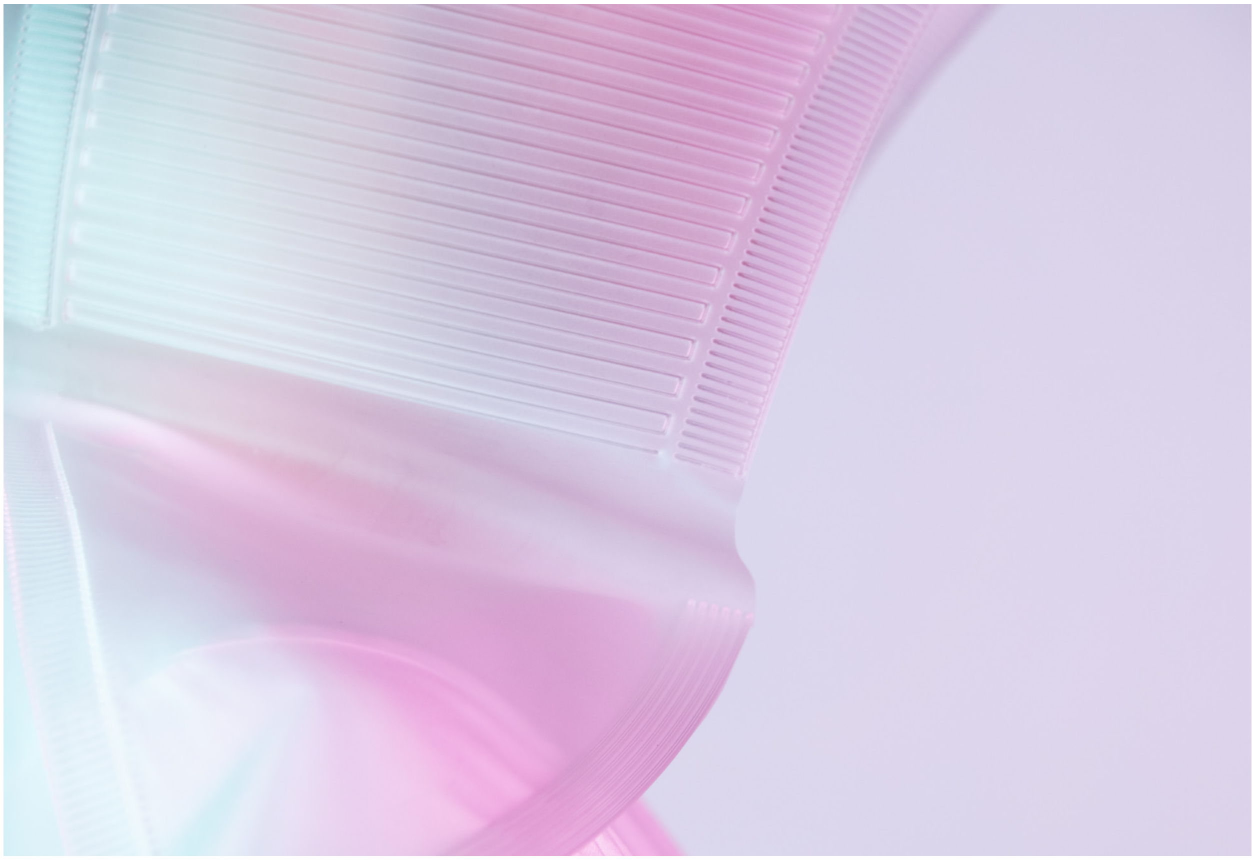
[23] “Zippppper Project,” nendo, accessed May 18, 2022, https://www.nendo.jp/en/works/zippppper-project/.



Chapter 4

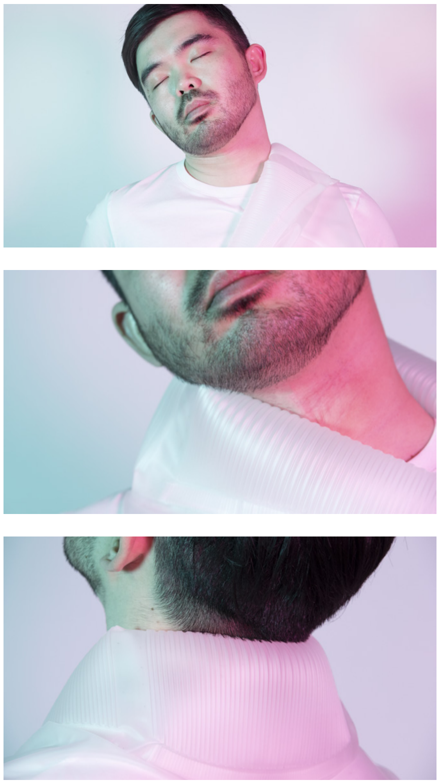
New Materialities of Flexibility

Therapeutic Garment

This next case study of a therapeutic garment is a more focused project of modifying the behavior of fabric, and perhaps more in line with the idea of a functionally graded material as mentioned in the previous chapter. With both iterations of the garment, the intention was to produce different states of flexibility and material interaction in the same object. The designs are flexible and fabric-like in their base format, but can be reconfigured to take on new form, volume, and structure.

The motivations for this design were personal, but hopefully result in something that is more widely applied. Having to manage chronic pain from a neck and shoulder injury, I am no stranger to all manner of therapeutic contraptions, from foam rollers and rubber balls, to endless variations of stretching and traction aids. Whilst these are mostly functionally effective in some manner, their designs leave a lot to be desired; they are typically clunky and rigid, and often beget the awkward decision of whether they should be left at home, unused, or brought along to the studio, or office, or even on vacation.

Folding some of the function of these therapeutic aids into the surface of a garment felt like an elegant way to circumvent this, whilst tapping into the provocative ability of fashion. In the two iterations of the design, line- and volume-based geometries are manipulated with flex zips to allow the same garment to be reconfigured into a hood, a collar, or simply as a therapeutic surface. In this transformation, the designs go from being pliable enough to be folded or rolled up, to providing enough resistance and rigidity for performing stretches and other therapeutic exercises.



Therapeutic garment being used for stretching and myofascial therapy

Previous Page:

Therapeutic garment being configured as a hood, with privacy screen

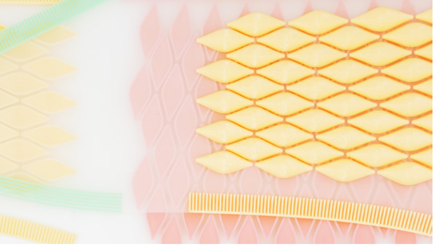
In terms of aesthetics, I had also intended for the designs to do double duty and express elements of the underlying issue and inspiration for this case study. The translucent lines of the first design riff off a history of transparency in cyberpunk-inspired fashion to form an isolating, privacy screen when the garment is configured as a hood. The soft pastels of the volumes in the second design, however, are a visual parallel to the tactile sensation of the garment.

Functionally, the two design iterations also diverge in how they achieve a change in flexibility. Despite being executed with a harder TPU (Shore 95A), the translucent, line-based design actually forms a softer volume when the garment is reconfigured. The lines act more like structural ribs to the TPU film, allowing for greater rigidity through additional thickness or an increased density of lines.

In contrast, the design with the colorful “bulbs” or “bumps”, leverages the use of geometry and a sealed air volume to create structure and a more rigid material behavior. What began as a desire to reproduce some of the surface of typical tools for myofascial massage, resulted in the somewhat accidental discovery of just how potent the adhesion of TPU is. The walls of the “bump” geometries are only 0.6 to 1.2mm thick, compared to the 2 to 2.5mm of the aforementioned lines, but with the air trapped in the printing process, it achieves a surprising level of rigidity when pressed. As the printed geometry is only in contact with the film along the perimeter of each shape, a lot of the flexibility of the film is retained along the plane of the surface.

Whilst I hope to eventually develop these designs into a fuller garment, such as a jacket or a raincoat, I think they are sufficient in demonstrating the gradient of material behavior possible alongside its expressive potential. Beyond a straightforward observation of material properties, I also believe this case study reaffirms the role of design in catalyzing these possibilities and the close relationship between designer, material and method. If we are able to rethink the design of an entire category of objects, that is, aids for physical therapy, how might we start to reframe more commonplace objects? Say, a chair? Or a helmet?

The chair, for one, might start to look very different from the unified, solid object that we are used to. Imagine, if you will, the reconfigurable volumes presented in this case study, but now strategically arrayed around a body. The selective design and deployment of these would now allow for all



From Top:

Garment worn as collar

Garment being actuated for shoulder support

Second iteration of the garment ased on bump geometries different manners of sitting. Integrating some into your favorite hiking pants might create a portable field “chair”. They might allow one to lie comfortably across a flight of steps, or lounge on a jagged rock beach.

Though admittedly just a little silly, these ideas do underscore how variably flexible material can be used to further reimagine otherwise static definitions of objects. They can also provide a kind of intermediary architecture with which we can have new interactions with the broader built environment, and the world around us.

Sliding flex zips allow for the collar to be adjusted for fit

Detail - Creating Volume(s)

The next detail that I would like to focus on are the bump-like volumes from this case study. Similar to the “spine” of the flex zips, the specifics of the geometry were actually developed in response to the constraint of working with extruded TPU filament. As mentioned in Chapter Two, the low viscosity of heated TPU is such that it does not have much capacity to bridge,[24] or for steep overhang angles.[25] Softer TPUs might even be too pliable in solid form to reliably produce geometries with thin walls and shells as freshly printed filament might easily deform the layers below it.

A more conventional 3D printing approach might rely on infill[26] or internal supports[27] to increase the rigidity of the print and reduce the span of bridging required. With the film or fabric substrate, however, neither of those are possible as these auxiliary geometries would simply be stuck inside of the printed volume. My approach, then, was in the spirit of corbelled arches, where the geometries of the volume were designed to be at the limit of an acceptable overhang or cantilever, up until the material is able to span across and seal the volume.

Creating this volume, whilst retaining some of the flexibility of the base film, is somewhat of a balancing act. If the shell of the volume is too soft and thin, it might require an excessively conservative overhang angle to be reliably printed. Too thick, however, and the contrasting rigidity of the volume against the film can force the film to tear or even cause the print to delaminate when manipulated.

The design of the garment features volumes of roughly the same shape and size, but it should be noted that many other

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24. Tobias Hullette, “3D Printing Bridging: 6 Tips for Perfect Bridges,” All3DP, August 13, 2021, https://all3dp.com/2/bridging-3d-printing-tips-tricks-for-perfect-bridges/.

25. Hironori Kondo, “3D Printing Overhang: How to 3D Print Overhangs,” All3DP, June 16, 2021, https://all3dp.com/2/3d-printing-overhang-how-to-master-overhangs-exceeding-45/.

26. Jackson O’Connell, “3D Printing Infill: The Basics Simply Explained,” All3DP, February 24, 2022, https://all3dp.com/2/infill-3d-printing-what-it-means-and-how-to-use-it/.

27. Dibya Chakravorty, “3D Printing Supports – The Ultimate Guide,” All3DP, November 5, 2021, https://all3dp.com/1/3d-printing-support-structures/.

variations are possible, with each producing slightly different behaviors. Larger volumes logically produce a large radius of bending with the overall surface, although this, too, is complicated by how each volume is compressed against another. Changing the ratios of length, width, and height of these geometries can also result in directional flexibility in the 2.5D material. In this example, the grid of elongated volumes easily rolls up in one orientation, but creates significant rigidity in the other.

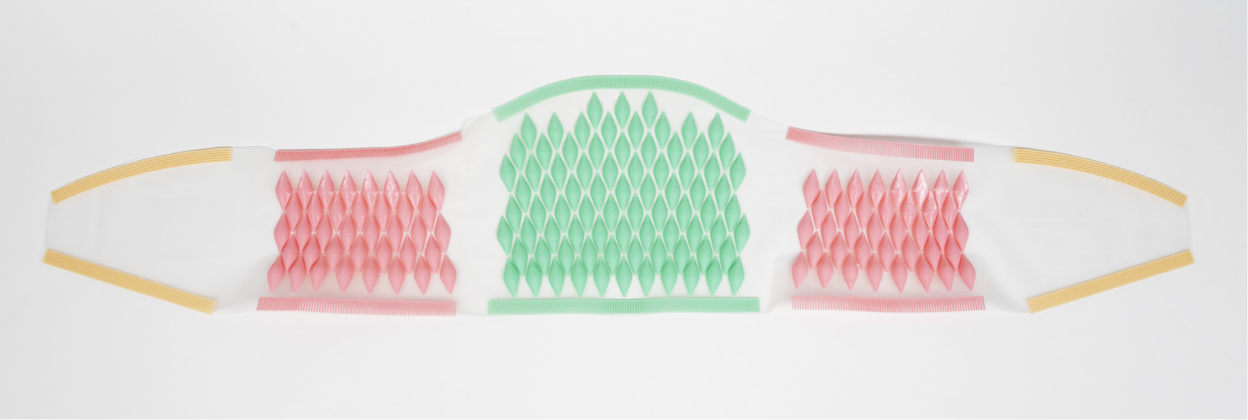
Chronologically, this detail was developed rather early on in this thesis, and could benefit from renewed experimentation and additional technical experience with the fabrication process. Beyond that, future research along this trajectory might investigate how these volumes and structures interact with a separate structural system, particularly one with active bending properties. Establishing a reliable means of modeling and estimating the flexibility or rigidity of these designs would also be crucial in enabling an exploration of this detail at larger scales.

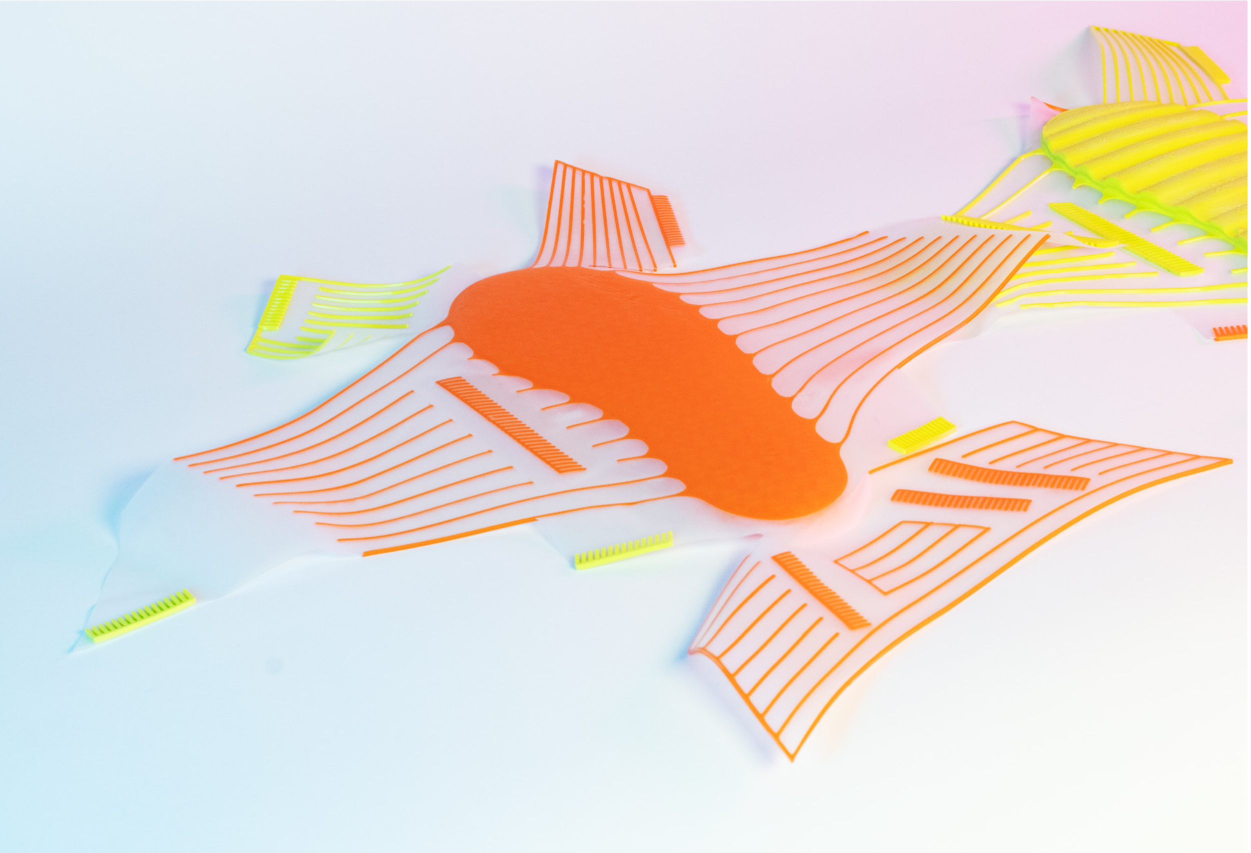
Below:

Two therapeutic garment designs in their flat formats

Next Page:

The same therapeutic garments are activated with the flex zips to take on volume and structure





Chapter 5

Custom Fit and Print-in-Place

Single Pattern Shoe

This last case study is of a single pattern shoe, designed to demonstrate a potential for individually customized objects, alongside an approach to streamlining manufacture and assembly with a single process. In the resultant single-piece design, a series of strategically placed flex zips serve to activate adjacent rib-like geometry and transform a relatively flat object into the shape of a shoe.

The shoe provides a challenging design object for 2.5D to address, not just for its complex geometry, but with its demands for volume, structure and function. Additionally, it boasts a rich tradition of design that spans the gamut of sports and performance wear, to fashion statement pieces. With the plethora of styles and types of footwear available, it may be hard to gather a definitive process by which shoes are made, but I have found a video by John Santos which offers good insight into just how much effort goes into making a pair of shoes.[28]

Process of going from a 3D scan model of the foot to a shoe last design

Previous Page:

Single piece shoe design in its flat form, and configured into a shoe

In this video, Santos walks viewers through the manufacturing process of a single shoe model in a factory in Leon, Mexico This process typically begins with the machining of a mold for the injection molding of the outsole. Here, a unique mold is required for each predetermined size of the shoe, with additional tooling of the mold done manually. This particular shoe model also receives a metallic detail before the injection process.

Depending on the volume of the production run, the fabric for the shoe upper is either laser-cut, for lower volume or limited runs, or die cut to achieve higher outputs. What follows is multiple steps of gluing and sewing to attach the layers of fabric together into an assembled upper. After this is completed, the upper is press-fit around a shoe last, and then stretched by hand to match the shape of the sole. Then, another round of gluing takes place, this time to attach the sole to the upper, with adhesion often aided by a pressure sealing machine. Lastly, the insoles are glued in, before the shoes are packaged into individual boxes for distribution and retail.

From the video, it is evident that a wide range of specialized machines are required for this process, alongside an army of skilled workers to effectively use them. With the injection mold, cutting die and shoe last, we can also observe a series of auxiliary objects that are specific to a particular shoe size. This, together with their associated costs, make any process of fit customization very challenging. At the end of this laborious and complicated process, there is also a certain irony that the finished shoes ship with a considerable volume of air in the box. It is these challenges of assembly and logistics that this case study seeks to address.

Beyond this conventional process of manufacturing a shoe, it should be of no surprise that 3D printing is no stranger to shoe design. Many different technologies of additive manufacturing have been brought to bear on parts of or even entire shoes, exhibiting an exhilarating breadth of design and an increasing sophistication of material use.[29] [30] [31] Whilst not all of these designs deliver on this potential, it should be noted that the shoe is a perfect opportunity for another of additive manufacturing's latent promises; of endless parametric variation and complete, personalized customization. That said, this case study is not intended to be an exemplar of additive technologies, but rather a comprehensive approach that uses at-hand technologies to create a custom-fitted shoe in a novel, streamlined process.

The process of designing this shoe began with the generation of a custom shoe last based on my own feet. In perhaps an indication of just how commonplace this process may soon become, all of the software used to design the shoe last were either open-source, or already available to consumers. First, a 3D scan of the author's foot was compiled with a mobile phone camera, using an off-the-shelf application, PolyCam.[32] This model was then input into the Rhino plug-in Shoe Last Maker,[33] which gathered all the required measurements of the foot and generated the corresponding shoe last. The last was then used in the process of developing a suitable pattern for the general flat outline of the shoe,

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28. John Santos, How To Make Shoes | Custom Sneakers From The Sole Up - YouTube, accessed May 2, 2022, https://www.youtube.com/watch?t=210&v=nSOt-H2kxmM&feature=youtu.be&ab_channel=JohnSantos.

29. Anna Spiewak, "3D Drawing Disrupts Shoe Production with More Efficiency," May 2017, https://www.basf.com/us/en/media/featured-articles/Technology/Reebok-Liquid-Speed.html.

30. Anas Essop, "PEAK Sports Launches 'The Next' 3D Printed Footwear with Farsoon Technologies," 3D Printing Industry, October 23, 2019, https://3dprintingindustry.com/news/peak-sports-launches-the-next-3d-printed-footwear-with-farsoon-technologies-163798/.

31. Fionn Corcoran-Tadd et al., "Our New Textile Innovation: Meet FUTURECRAFT.STRUNG," adidas US, June 2021, https://www.adidas.com/us/blog/562694-our-new-textile-innovation-meet-futurecraftstrung.

32. Polycam - LiDAR 3D Scanner (Polycam), accessed May 18, 2022, https://poly.cam/.

33. Podohub, Shoe Last Design Software: Shoe Last Maker (Podohub, 2021), https://shoelastmaker.com/shoe-last-design-software/.

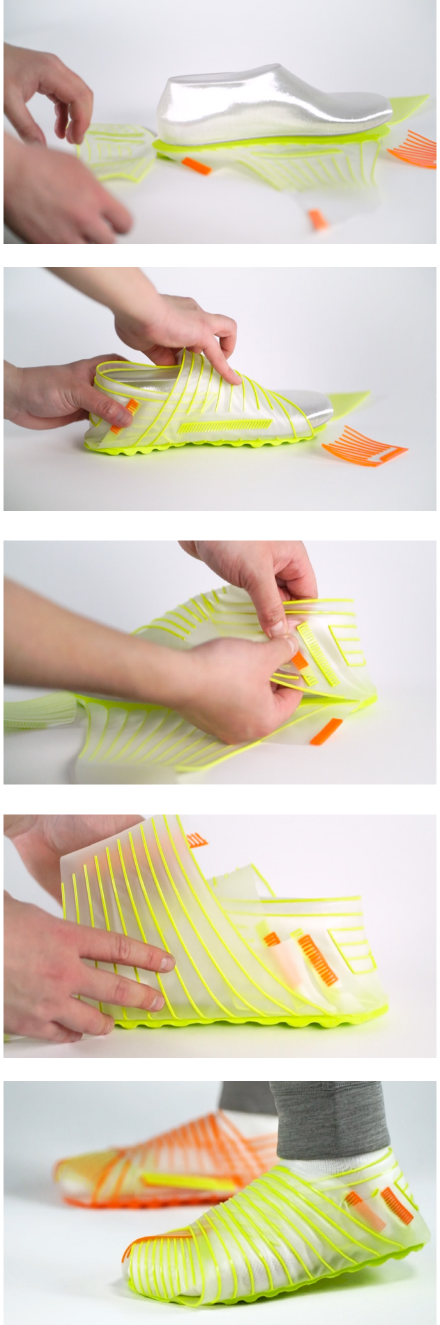
and the form that it took.

Given the broad typologies of foot and shoe shapes, and a fair amount of expertise in relating that to last geometry, it is not a stretch to imagine how this initial process might be parameterized and at least partially automated. Here, the physical last is more of a demonstration of the utility of existing technologies to designers wanting to develop custom-fit objects, and for me to more rapidly prototype shoe patterns.

The development of the fabric pattern into the final shoe design followed three general steps. First, the 3D-printed geometry was designed to provide the necessary functions of attachment and structure, as well as to complement the aesthetic sensibilities of a one-piece pattern.
With the former, a series of strategically placed flex zips were employed on both sides of the pattern in conjunction with a geometry similar to that of the line-based garment design in Chapter Four. Additionally, subdivision surface geometry was used to create continuous material from the sole of the shoe through to the main structure and connecting "wings" of the design.

Similar to the process of the tote bags, the next step was to optimize this geometry for printing. The Voron printer was used for the shoe design, due its larger bed dimensions (350mm by 350mm) as well as its capacity for faster TPU printing. By this stage of the thesis, I had also advanced my fabrication technique to allow for a much smaller printhead clearance. As such, the design benefited from geometries that were in close proximity to that on the reverse side of the pattern, thus creating a more seamless appearance. This interesting distinction of one side of the print from the other was preserved, however, with a didactic, two-tone color scheme.

The last step of the design process was to actually to fabricate a version of the shoe, so as to iterate over the design. As noted in the previous case studies, much of the geometries and behavior of the designs were experimentally determined, owing much to the unique interaction of the flexible TPU filament and film. As such, adjustments to the base pattern had to be made for fit, with "slack" added or removed by redrawing the perimeter line of the pattern. The thickness and density of the printed elements were also altered in response to changes in the pattern, and to modify the flexibility of specific parts of the shoe.



Video stills illustrating the process of configuring and wearing the shoes

The resultant shoe design effectively fulfills the goals set for this case study; it fits well to both the shoe last and my foot, with a pair being able to be printed within a day on a single 3D printer. The design also offers some flexibility in how this technique might be implemented at a consumer level. Unconfigured, the shoe is relatively flat and can be easily shipped in an envelope from a more centralized production location. Alternatively, it is also not difficult to envision a flagship store that has the required scanning and printing capabilities to be able to take an order for a tailored shoe on one day, with it ready by the next.

Detail - Dual-sided printing, bonding

One of the conceits of the shoe design, is that whilst it does combine the outsole and upper, the reverse side of the outsole is mostly flat. This makes it challenging for the design in its current state to properly accommodate an insole or a midsole. A possible solution to this is to include a concavity on the opposite side of the outsole, supported with removable material as it is printed. This does, however, increase the post-processing required for the design, and may not yield reliable prints.

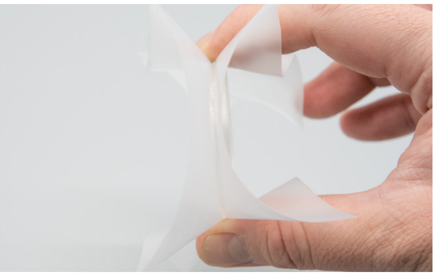
An alternative solution to this, that I have only just begun to experiment with, is for true, dual-sided printing. Whilst the shoe and bag designs have 3D printed elements applied to both sides of a fabric, the sample pictured here exhibits something entirely different. With this, the printed elements on either side occupy the same area on the fabric, seemingly going through the surface. This is achieved by either inserting the fabric during a specified pause in the print, or by turning an already printed portion over, and printing with an offset in the vertical direction. While this may prove challenging in terms of registering the workpiece or securing it, it does offer some intriguing possibilities for design.

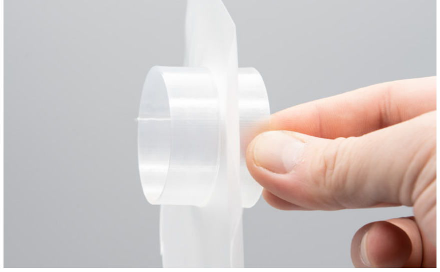
In the inverse of this, I have also found that it is possible to use printed TPU to bond and seal layers of TPU film. This is perhaps less surprising, as the material is regularly heat-sealed when used to create volumes for fluids. It does, however, enable us to expand upon the techniques used in this thesis. For example, this might allow for more complex, layered designs, and also ones with multiple fabric types. When seen as an analogue to sewing with thread, it might

From Top:

Material sample that bonds multiple layers of TPU film with 3D printing

Two views of the same material sample that has been printed on both sides of a TPU film

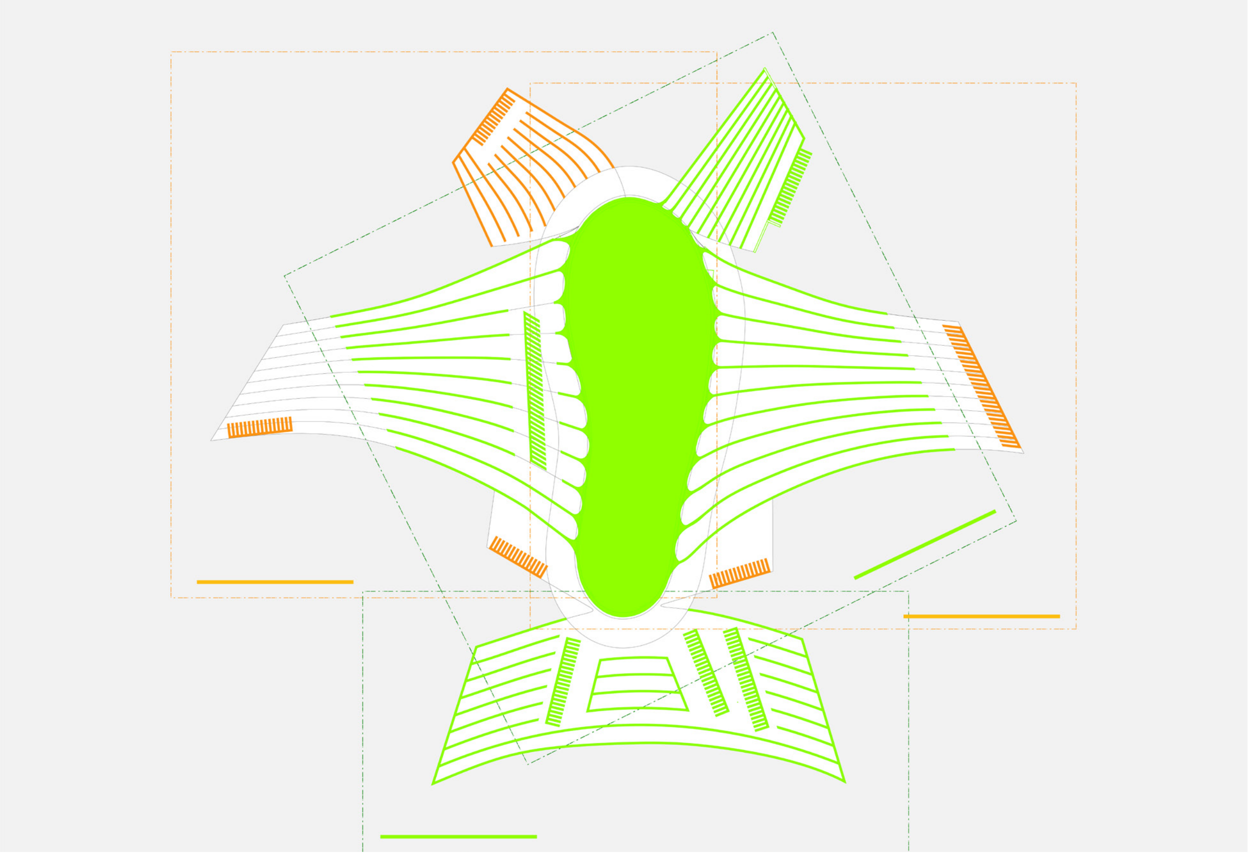


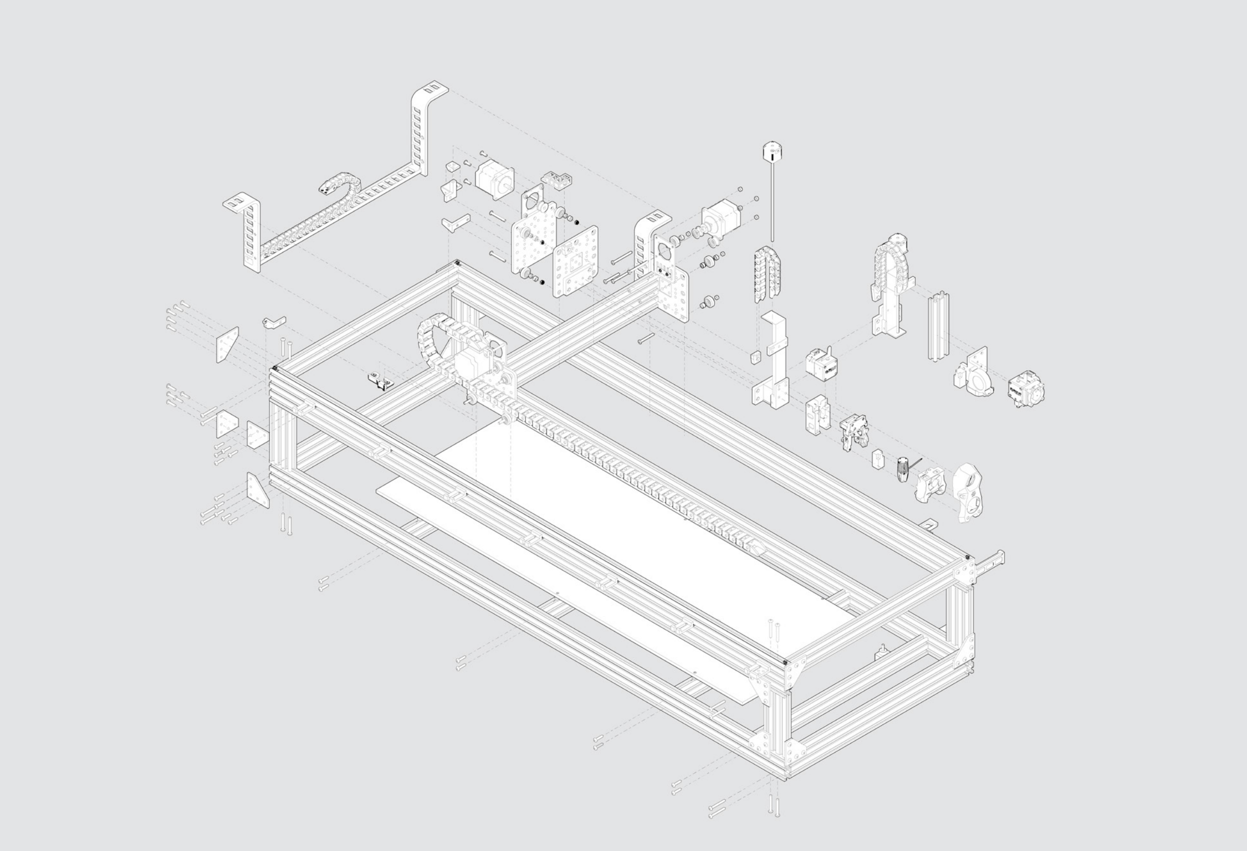


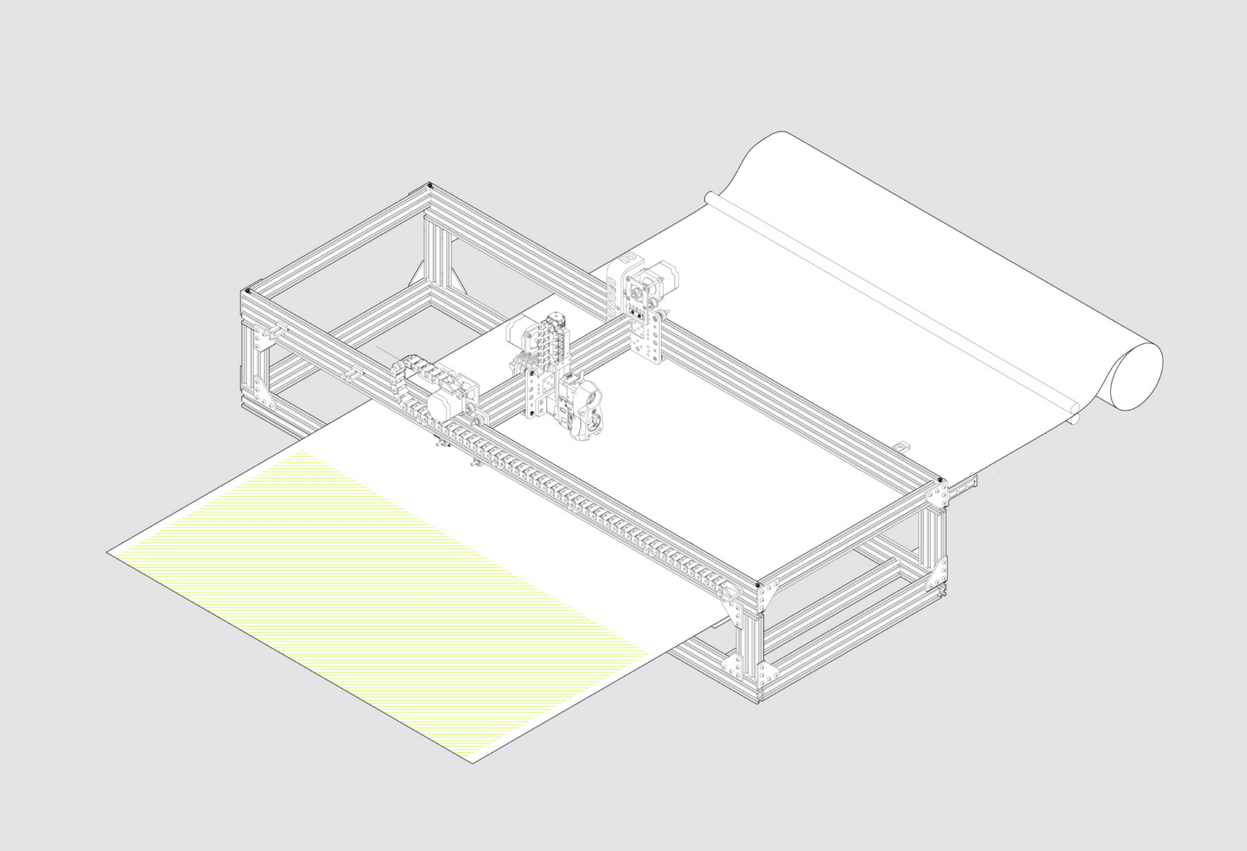
also inspire a kind of translation of sewing techniques, such as with the shaping of fabrics with curved seams, or even pleats.

Of the details explicated in the case studies, these are undoubtedly the most undeveloped. Much of the reliability of executing them will come down to machine-specific adjustments of speed and temperature for each moment that the two materials interface. That said, I believe that it is these two details that present the most potential for future 2.5D designs, allowing for greater geometric complexity, but more importantly, for an opportunity to build upon the extensive repertoire of techniques from more conventional fabric work.

Process drawing for planning the design and fabrication of the single pattern shoe







Chapter 6

Design of a Roll-to-Roll 3D Printer

Parallel to the case studies, this thesis also pursued the design and assembly of a prototype, wide-format 3D printer. Responding to design constraints faced with the bag, garment and shoe, this printer was specifically intended to accommodate standard widths of roll fabrics in its print area, whilst performing equal or better than the printers I had access to. With further iterations, it may also be possible to automate the movement of the fabric, extending the limits of designs in that dimension.

Previous Page:

Exploded axonometric drawing of the roll-to-roll 3D Printer

Schematic of how the printer would accommodate standard fabric widths

There is the intent to more thoroughly document the design and assembly of this printer at a later date, and to publish that information in a public, online repository.[34] Thus, this chapter will instead provide an overview of design decisions, as well as a summary of its key specifications.

Current 3D Printer Paradigms

It should be noted that other 3D printer designs with an elongated axis do exist. However, a majority of them involve an increased Z-axis range, particularly achievable with delta robot kinematics, as well as CoreXY or H-Bot setups that have a moving print bed. In a search of both open-source or commercial solutions, the designs that came closest to what I was envisioning were industrial printers by WASP[35] , Modix[36] and BigRep[37] . Even then, the emphases of these machines are typically on a large build volume, and, as such, few models have a X or Y axis span appropriate for standard fabric widths. Arguably, if the work of this thesis is to be scaled up, whether in physical dimension or production output, it would require a rethinking of current 3D printer designs.

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[34] En-Han Thaddeus Lee, 2.5D_BigBoiPrinter, 2022, https://github.com/leeetthad/2.5D_BigBoiPrinter.

[35] WASP, “Delta WASP 2040 INDUSTRIAL X | Industrial Delta Printer,” accessed May 18, 2022, https://www.3dwasp.com/en/delta-wasp-2040-industrial-x-industrial-delta-printer/.

[36] Modix, “Modix Large 3D Printers,” accessed May 18, 2022, https://www.modix3d.com/.

[37] BigRep, “Large-Format 3D Printers: Industrial & Professional | BigRep,” August 6, 2018, https://bigrep.com/.

Open-sourced

To design this printer, I instead turned to open-source solutions, not in terms of complete designs, but on the level of specific components. This is perhaps an opportune moment to acknowledge that much of the work of this thesis would not have been possible without a vibrant, open-source 3D printing community. From the 3D printing hardware, to the slicing software for generating G-code, to the software that operates the printers with this code; all of it has been open-source.[38] With how acquainted I have gotten with this body of knowledge, it has greatly informed the design of this printer.

It would probably do well to also clarify that the ambition of this exercise was not to design a 3D printer completely from scratch. Many of the 3D printers associated with the RepRap movement were designed around its core tenet for a self-replicating machine. As such, these devices utilize as many 3D printed parts and mechanisms as possible, allowing its users to then use them to produce another machine. This genre of machines does have a lot of potential and have inspired the research of this thesis[39] [40], but they are simply not the focus of this chapter.

In contrast, this prototype is intended to illustrate a paradigm of machine design that will allow designers to work with industry-standard widths of roll fabric. Thus, instead of proposing a ground-up redesign of all the parts of a 3D printer, this design adopts elements of existing open-source designs, as well as some generic, ready-made assemblies. The reader, if keen to build this machine, may just as easily replace some of the components with compatible ones, whilst still preserving the ethos of the design. A summary of the specifications of the printer is provided in the appendix.

Kinematics

With any machine design, there are invariably decisions made to prioritize certain capabilities, and with that, associated tradeoffs and limitations. With a knock-on effect, the primary considerations for the kinematics of this printer have been span, mass, and speed. The goal of this design to accommodate fabrics with widths of about 40 to 50

[38] For a summary of the specific hardware and software used, refer to Appendix 2

[39] The Clank is a good example of a ground-up RepRap project with many advanced features.

[40] Jake Read, “About the Clank Project,” Clank, accessed May 18, 2022, https://clank.tools/about/.

inches has informed a lot of these choices concerning these factors. Instead of delving into calculations and technical specificities, I will discuss this in relation to the methods of this thesis and any associated design constraints.

Span

With a sizable span in one axis, deflection becomes the primary concern for any motion system intended for fused filament fabrication. Given that the process often requires precision down to around 0.1mm or less, that elongated axis should be designed with sufficient rigidity.

Mass

Excessive deflection on the long axis can typically be mitigated in one of two ways, either by implementing a better support structure for the axis, or by reducing the intended load on the axis in the first place. The first solution often comes at the cost of increased overall mass, or of weight applied to any supporting axes. The mass of structural and actuation components ultimately adds up, particularly when we consider the kinematics being adopted.

Speed

The mass of the components moving along the toolpath also has a knock-on effect on the speeds possible for FFF. As a benchmark, I designed this printer to match or even outperform the Voron printer I was using. For reference, the Voron moves at a linear speed of 350mm/s and with accelerations of around 3000mmv/s2.[41] [42] This is considered a moderately fast standard of printing, even when compared to industrial solutions.

This printer design strikes a balance between these three parameters of span, mass, and speed, by first accepting the tradeoff of a limited Z-axis stroke of around 100mm to 150mm. In turn, this offers the advantage of greatly reducing the mass that is being moved along the toolpath in a Cartesian system.[43] With the designs and techniques I have developed in this thesis, giving up some of that range in the vertical direction did not seem particularly detrimental.

Some other kinematics[44] [45] were initially considered, in particular, CoreXY and a rolling gantry with unlimited travel in one axis. Implementing a CoreXY configuration with the elongated axis would primarily result in issues of increased

41. Particularly adventurous open-source designers, like the Vez3D team, have managed more than twice those speeds with similar, DIY CoreXY setups. The exceptional performance of their VzBot is well documented.

42. Simon Vez, VzBoT (2021; repr., VzBoT, 2022), https://github.com/VzBoT3D/VzBoT-Vz330.

43. This reduced mass is important as it not only allows for faster print speeds, but reduces the amount of vibration experienced by the machine. This vibration often has a significant impact on the visual quality of the 3D print.

44. The 3D Printing Blog 3DP offers a good summary of some common kinematics used in FDM

45. Jackson O'Connell, "The Types of FDM 3D Printers in 2022 (Cartesian, CoreXY, & More)," All3DP, April 23, 2022, https://all3dp.com/2/cartesian-3d-printer-delta-scara-belt-corexy-polar/.

mass and backlash. Moving the CoreXY gantry up and down in the vertical direction would result in a large mass moving with the toolpath. Moreover, this elongated gantry would require excessively long timing belts, increasing the degree of play in the motion system.

The rolling gantry, like that implemented with the Textile Drawing Machine open hardware project, is an intriguing proposition that is well suited to the needs of fabrication in this thesis. In essence, it is a machine design that spans only across one axis of the work plane, relying on wheels on either side of this span to move it infinitely in the other direction. A more precise rendition of the gantry would probably be appropriate for another variation of this printer, but was avoided in this design due to concerns about its repeatability and also its precision in the Z-axis.

With this consideration of span, mass and speed, a belt-and-pinion system made of linear actuators by OpenBuilds[46] and a generic lead screw actuator were chosen for the overall motion control. Additionally, this choice offered high precision, high repeatability, and affordability. Of the other linear actuators considered, it is worth pointing out that a system of ballscrews and linear rails would perform more reliably and efficiently, but perhaps be better suited to an industrial iteration of this machine as they are significantly heavier and costlier.

Extruder and Print Bed

The potential afforded by the motion system would not mean much without an accompanying extruder system suited to printing TPU and other flexible filaments. For this, the design offers two options for the extruder assembly, with details listed in the summary below. Both employ a dual-gear extruder motor, and exhibit a completely supported filament path. The rationale for these in regard to TPU filament were explained in Chapter 2. Additionally, the printer design includes modified parts for the Z-axis assembly that can accommodate a modular change of the extruder assembly, allowing for future upgrades or for extruder setups more suited to specific filaments.

Similarly, having a low level of deflection in the elongated axis would not be meaningful if the print bed itself has too large of a variance in its flatness. With no requirement for

[46] OpenBuilds, "OpenBuilds," GitHub, accessed May 2, 2022, https://github.com/OpenBuilds.

bed heating in the methodology of this thesis, there are potentially many options to achieve this, including beds made of glass or garolite. For the assembled printer, I chose a cast aluminum tool plate (ATP5) that had a reasonable flatness of 0.015" per foot.

Electronics and Software

There are many possible configurations of electronics and software to operate this printer, but here are some of the features of my chosen setup that have helped greatly in meeting some of the performance requirements listed above as well as the demands of the methodology of this thesis.

With the electronics, the capacity for high voltage drivers on the printer MCU was paramount, as it allowed for the use of stronger, and faster, stepper motors. Coupled with inbuilt software functions, the TMC5160 and TMC2209 also achieved a fine level of microstepping[47] [48] with the motors, and thus, detail in the geometries. The software is even advanced enough to compensate for significant vibrations and standing frequencies in the hardware,[49] improving the quality of the print and minimizing the need for post-processing of the object.

With the precision required in FFF, coupled with the need to print on film or fabric that are 0.05mm to 0.2mm thick, it is challenging to achieve consistent printing just with a well-calibrated motion system. Here, an advanced bed mesh calibration model - implemented as part of the Klipper firmware - has proved instrumental in helping to automatically account for any height variances on the print surface. This calibration model is generated by first getting the print head to sample a matrix of points on the build surface with an inductive, magnetic, or mechanical switch. The executed G-code is then altered on the fly by the firmware according to the relative changes in height at those points.

Some other features of the electronics and software that have proven helpful are also noted in Appendix 3.

Future Use and Development

What ultimately began with the desire to work more effi-

47. Trinamic, "TMC5160 Datasheet," Trinamic, accessed May 18, 2022, https://www.trinamic.com/products/integrated-circuits/details/tmc5160/.

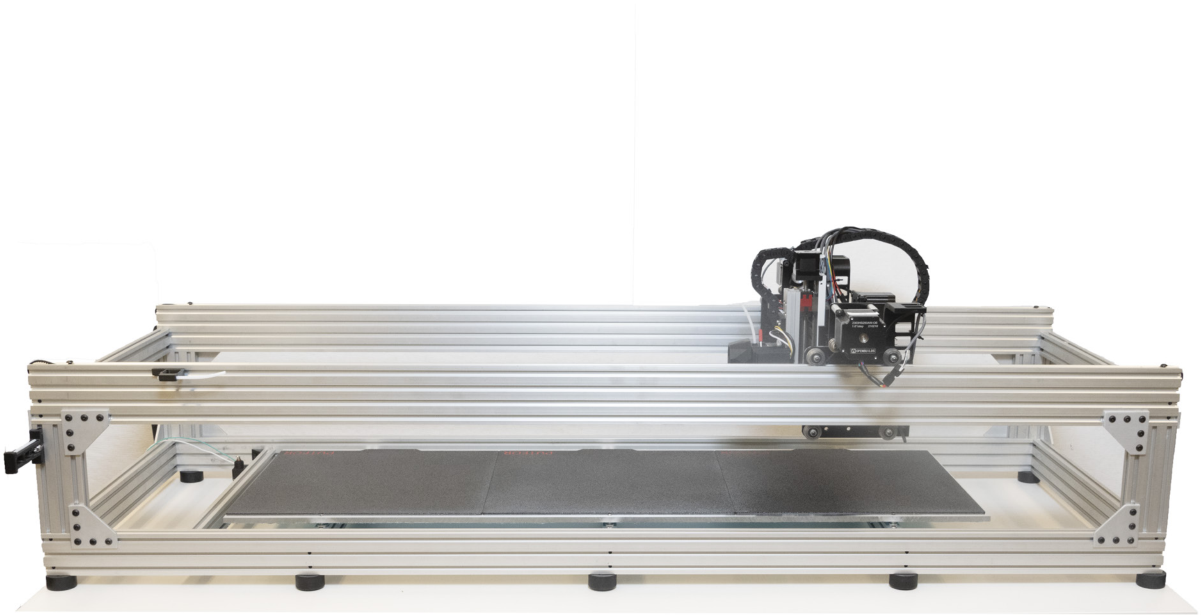
48. Trinamic, "TMC2209 Datasheet," accessed May 18, 2022, https://www.trinamic.com/products/integrated-circuits/details/tmc2209-la/.

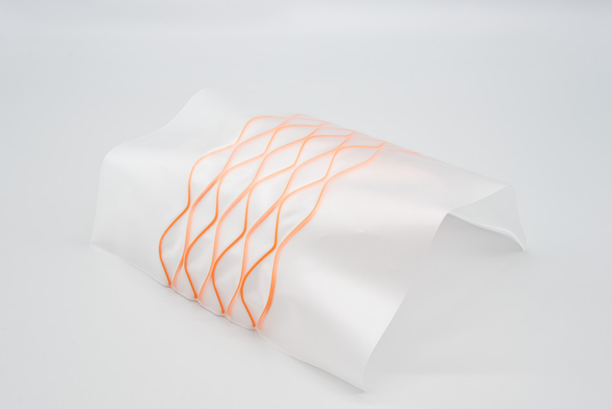
49. Kevin O'Connor, "Resonance Compensation - Klipper Documentation," accessed May 18, 2022, https://www.klipper3d.org/Resonance_Compensation.html.

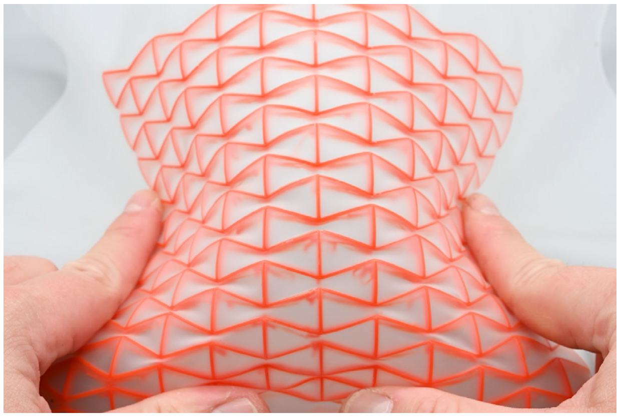
ciently with roll fabrics has resulted in a trajectory of research that begins to touch upon more specific domains of expertise, such as machine design engineering and materials engineering. A practical application of the principles of this printer on an industrial scale will probably require collaboration with experts from these fields, and probably significant revisions to accommodate industrial standards and technologies.

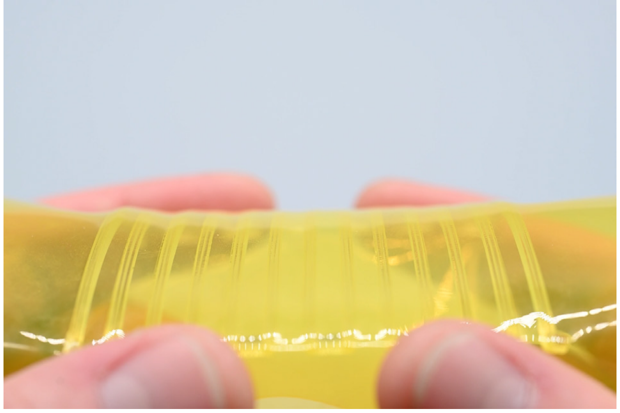
Suffice to say, this exercise of developing a design for a wide-format printer has served its primary purposes. It is significant in enabling further research beyond this thesis, allowing for me to work with printed designs at larger scales. This broadens the vocabulary of my design approach, whilst providing new categories of objects and functions to design for. The documentation of its assembly and use will hopefully also gather sufficient evidence to argue for a change in paradigm for how FFF machines might be designed and used.

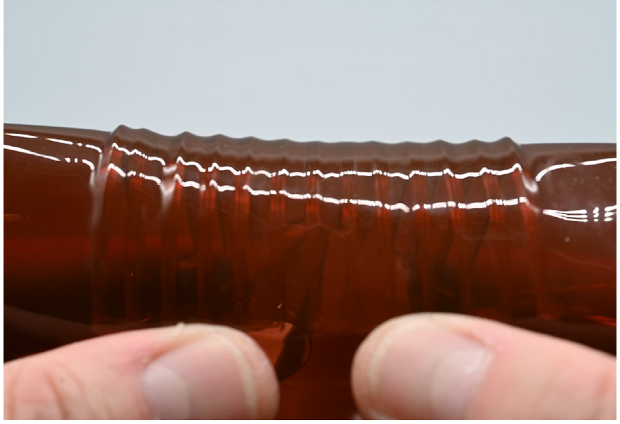
Elevation view of the assembled 3D printer design











Chapter 7

Beyond 2.5D

Contributions

One of the main contributions of this thesis is a comprehensive vocabulary of fabrication techniques and material interactions that will allow for novel implementations of additive manufacturing to expand on what is possible with existing two-dimensional, sheet and roll material processes.

To recapitulate, I put forth three main benefits for doing so through the case studies. First, the reformable bag in Chapter 3 demonstrates possibilities for modifying fabric behavior. The materials and details introduced allow for variable reshaping of fabric and for new ways to connect fabric and 3D-printed objects.

In Chapter 4, the garment presents a new materiality of flexibility that is possible with the novel combination of materials and the judicious design of their geometries. Its result is a rethinking of how we might design objects to take on volume and rigidity, only as when we need them.

The shoe design of Chapter 5 is a case study in how the techniques presented in this thesis can be used to develop customized objects in a streamlined manufacturing process. The intention for this is to leverage our expediency with two-dimensional design and manufacturing processes, and extend its capabilities to produce objects with complex geometries and structure.

On a more fundamental level, I also hope that this thesis serves as a positive example of how designers might critically engage with existing fabrication technologies and the relatively informal body of knowledge that is open-source 3D printing. Much of this research germinated during COVID-

Previous Page, from Top, left to right:

The first four images present the same material sample behaving in markedly different ways, being rolled up, configured into strcuture, and even supporting its own weight

Structure formed with 3D print on TPU-coated nylon

The last three images are of tests of TPU prints on new fabrics and film.

19-induced quarantine, where I was stuck at home with my Prusa printer, wondering just what it was capable of.

This process began first, with not accepting that the printer was limited to household knick-knacks or physically rendering some complex digital geometry for architectural representation. It persisted with the belief that the technology, even at the open-source, household level, was truly capable of enabling design that is novel and meaningful.

On a broader level, this research also advocates for design that is able to redefine the assumptions that we place on objects, to reimagine them in dynamic states, and to operate at various points in their production and life cycle. This might begin with expecting more from material interactions, and also overlap with the broader vision of self-assembling and programmable objects.[50] It will inevitably involve the design of how things are manufactured and transported, how they behave when in use or out of use, and at the end of their lifecycle, how they might be reclaimed, recycled or sustainably disposed of.

Future Dimensions

I will conclude the writing of this thesis by sharing some of the technologies that excite and inspire me and offer some speculation towards the future dimensions of this work.

Technological Possibilities

The particular technology of Fused Filament Fabrication (FFF) was originally chosen for its growing ubiquity and accessibility, and as such, the research was initially accompanied by the idea that some of its techniques may directly benefit anyone with a household 3D printer. As the research progressed, some of that aspiration persisted, but along with a growing acknowledgement that the materials and methodology used was starting to exceed the capabilities of a common low-cost 3D printer. However, I persisted with the use of the technology due to its affordability and the reliability of the material phenomena observed in fabrication.

With the rapid advancements being made across the broader spectrum of additive manufacturing, in continuing this

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[50] Skylar Tibbits, “4D Printing: Multi-Material Shape Change,” Architectural Design 84, no. 1 (2014): 116–21, https://doi.org/10.1002/ad.1710.

research, it would be prudent to take a moment to reassess some of its assumptions, and to ponder the exciting design possibilities of new technologies and materials.

Technologies directly adjacent to FFF or FDM already seem to provide meaningful ways to further this research. In terms of materials, there are new formulations of TPU filament that are worth consideration. One example is a TPU that has been designed with a foaming agent so that it exhibits variable Shore Hardness depending on the temperature of its extrusion.[51] [52] This would allow for designs of single geometries that behave differently at specific points in its design. Other types of TPU might also allow for a higher content of carbon from biomass and for better biodegradability, thereby improving the overall sustainability of its use.

Modifications to FDM processes would also enable new fabrication techniques, and by extension, possible geometries and designs. First, multi-material printing could be implemented in a number of ways. With a single extruder, the switching of filaments might be automated, so as to allow for multiple materials to be used in a single print. This might allow for the concurrent use of TPU filaments with different Shore hardness, or with different materials entirely. Examples of this technology that would work with the existing hardware setup are the Prusa Multi Material Upgrade (MMU)[53] and the open-source Enraged Rabbit Carrot Feeder (ERCF).[54]

One interesting possibility would be for the use of water-soluble PVA as a support material, allowing for greater spans of TPU, as well as more complex concavity where needed. The latter, in particular, would greatly benefit the development of the shoe design in Chapter 5. A mixing hotend, a more eccentric form of multi-material extruder, might also grant the ability to print a gradient of material by heating and blending two filament sources on the fly.

Other technologies could also allow for multi-material prints alongside more rapid printing. Automated, modular swapping of extruder assemblies, such as that in the opensource Clank[55], E3D ToolChanger[56] or Prusa XL[57], would permit the consecutive use of not just different materials, but different extruder nozzles within a single print. This would facilitate more versatile print speeds by, for example, using a large nozzle for broader and quicker stroke, but a much finer one to add detail as needed.

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51. colorFabb, "VarioShore TPU Is Available Now!," Learn ColorFabb (blog), October 11, 2019, https://learn.colorfabb.com/varioshore/.

52. Lubrizol 3DP Team, "Revolutionary Filament Makes 3D Printing of Foams a Reality - Lubrizol," March 8, 2020, https://www.lubrizol.com/3D-Printing/Blog/2020/07/colorFabb-expands-capabilities-of-3D-printers.

53. Prusa Research, MMU2, accessed May 18, 2022, https://github.com/prusa3d/Original-Prusa-i3.

54.Ette, EnragedRabbitProject, Python, 2022, https://github.com/Ette-Git/EnragedRabbitProject.

55. Jake Read, "Tool Changer and Tools," Clank, accessed May 18, 2022, https://clank.tools/tools/.

56. E3D, "ToolChanger," E3D Online, accessed May 18, 2022, https://e3d-online.com/pages/toolchanger.

57. Prusa Research, "Original Prusa XL | Original Prusa 3D Printers Directly from Josef Prusa," accessed May 18, 2022, https://www.prusa3d.com/product/original-prusa-xl-2/.

Independent dual extrusion, or IDEX[58] , is another implementation of multiple toolheads that is capable of more rapid and multi-material FFF printing. With this technology, two extruder assemblies move independently on an axis, each possibly using different materials, hotends, or nozzle types. The general idea is for a greater volume of material output, and also for the parallel production of multiples of a print, or of parts of the print. One could see how potent this technology could be with the longer axis of the roll-to-roll printer, and possibly even with more than just two independent extruders.

In rethinking the format of the raw material used in FDM, one might even forgo the usual filament with 1.75mm diameter. Filament with a diameter of 2.85mm, or even pelletized plastic could be considered, both greatly increasing the potential volumetric output of the printing process.

There is also the possibility of translating the techniques and designs of this thesis to additive manufacturing technologies beyond that of FFF or FDM. We will briefly discuss the possibilities for four of these technologies: Selective Laser Sintering (SLS), Stereolithography (SLA), liquid injection, and hybrid printing.

In both SLS and SLA, TPU has also been developed as a raw material, seeing extensive use in the production of 3D printed shoes.[59] [60] As the name suggests, with SLS a bed of powdered TPU is selectively fused into the desired geometries by a laser. In SLA, a high-powered laser is also used, but instead, to cure and solidify a TPU photopolymer. With how the thermal dimension of how the printed and film TPU interface, I would infer that SLS would be more suited to the techniques of this thesis, but that remains to be experimentally verified.

This thesis has not engaged with either of these technologies, mostly due to their higher costs, but also due to the lower "hackability" of the SLS and SLA machines that I had access to. That said, both SLS and SLA feature significantly faster and more detailed output as compared to FFF, and there is certainly the intention to explore these technologies in advancing this research.

Reebok Liquid Speed Shoe

Other more specialized processes could also offer interesting design prospects. For example, a form of high-volume, injection drawing has been developed by Reebok and BASF in their "Liquid Factory" series. This involves the extrusion

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[58] BCN3D, "IDEX Technology - BCN3D," BCN3D Technologies, accessed May 18, 2022, https://www.bcn3d.com/technology/.

[59] Essop, "PEAK Sports Launches 'The Next' 3D Printed Footwear with Farsoon Technologies."

[60] Formlabs, "Formlabs & New Balance: The Future of Performance Products With Customized Shoes," Formlabs, accessed May 18, 2022, https://formlabs.com/customer-stories/newbalance/.

of a polymer through a relatively large nozzle, onto a flat or curved build plate. While I was not aware of this concept when designing the shoe case study, they function in a similar way. The Liquid Factory process does not print directly onto a substrate, but has the advantage of more rapidly producing the structures needed for a shoe.

The last technology we will discuss is possibly also the most exciting. What if we applied additive manufacturing not only to the printed TPU, but to the substrate it is printed on? Some commercial examples offer an insight into what a 3D-knit fabric might look like. Uniqlo and Shima Seiki have collaborated to create seamless garments that are able to be made in a single machine, with minimal waste.[61] [62] Adidas' Futurecraft.Strung takes the concept further, using robotic knitting for customized shoe uppers.[63] Blending conventional fabric processes with selective 3D printing and 3D knitting could provide dizzying dimensions of material interaction and designed behavior.

Next Steps

Descending from such heady speculation, I would like to propose some more immediate, but equally meaningful avenues to further the work of this thesis. After the discussion at my final presentation of this thesis, I was particularly inspired to think about how the case studies could be developed into separate offshoot projects.

The tote bag is sufficiently pragmatic and of an appropriate scale to be the subject of a community-oriented education project. Beyond an online repository or forum, this might take the form of workshops in local makerspaces or schools that have basic and affordable FFF printers. Relying on the bag as a relatable object, these workshops would be a good format for people to learn some of the techniques of this thesis, as well as to develop some of their own.

The therapeutic garment would be the subject of a more design- or aesthetics-oriented project. Extending the design of the hood or collar into a fuller garment also brings into focus a personal, re-deployable architecture. This would take advantage of the synergy between fashion and architecture to design wearables for function, agency, and expression.

In a much more pragmatic vein, the single-pattern shoe is

[61] Uniqlo, “What Is 3D Knit? (And Other Important Questions),” UNIQLO TODAY | UNIQLO US, accessed May 18, 2022, https://www.uniqlo.com/us/en/news/topics/2018090601/.

[62] Shima Seiki, “I ⍰ WHOLEGARMENT | SHIMA SEIKI | Computerized Flat Knitting Machines, Design Systems, CAD/CAM Systems,” accessed May 18, 2022, https://www.shimaseiki.com/wholegarment/love/.

[63] Corcoran-Tadd et al., “Our New Textile Innovation.”

ripe for development into a more complete product. Further research would be required to improve the shoe's equivalents of the toecap, insole, and midsole, as well as to apply the principles of the wide-format printer at the small to medium industrial scale.

Postlude

In the midst of such a sweeping and ambitious project, it has often been challenging for me to evaluate and articulate the design work in the lexicon of architecture. After braving the entirety of this writing, the reader may be intrigued to know that one of the inspirations for this work was, and still is, wallpaper. Allow me to explain.

Wallpaper, at least in my mind, has always been a proto-2.5D. It is, by necessity, an abstraction, whether of pattern, still life or texture, but also just barely a substance. It is successful in its dematerialization of the wall by being a part of the wall itself, so thin as nearly not to be a distinct thing beyond its appearance. After such a steady focus on material, it is a little awkward to acknowledge that in this dematerialization, wallpaper elegantly accomplishes two vital things. It is intuitive, and it provides agency; two attributes that I humbly suggest the designs of this thesis also achieve.

Despite its varying relevance to architecture across the years, wallpaper inevitably conditions and alters the space it is in with its semiotic potential. It is a surface that situates the viewer not only in space, but within social and historical contexts through its reference to a larger, abstract system. This function is dynamic and intuitive, as wallpaper is only as relevant as the social cachet its appearance might garner.

If anything, the ebb and flow of wallpaper's fashionability, and the relative ease of its replacement, grant the occupant something that "proper" architecture sometimes struggles to provide: agency. A better home interior, if only just superficially, establishes a whole new social, and financial, identity for the family. It is the promise of an architecture that is paper thin.

It is this dimension of architecture that I ultimately hope my designs continue to live up to.

Glossary

Bowden

A configuration of FDM printer where the extruder motor is stationary, and pushes the filament to the moving hotend.

Direct Drive

A configuration of FDM printer where the extruder motor moves with the hotend

Extrusion Flow

Usually expressed as a percentage of the nozzle diameter. Measurement of how much filament is extruded from the nozzle

Extrusion Width

Usually measured in millimeters. Often interchangeable with extrusion flow in slicer software settings

FDM

Fused Deposition Modeling. A type of additive manufacturing process where plastic filament or pellets are melted and deposited in a controlled manner.

FFF

Fused Filament Fabrication. A subset of FDM only using filaments.

Filament path

The length that the filament travels from the extruder motor to the hotend.

G-code

Basic programming language used to operate Computerized Numerical Control machines

Hotend

The component of an FDM machine that heats up the plastic. It typically consists of a heating element, a heatbreak, and a thermistor. It also accommodates a nozzle for the extrusion of the heated plastic.

RepRap

An abbreviation for Replicating Rapid-prototyper. Also the eponymous open-source movement that seeks to design additive manufacturing machines that can self-replicate

Shoe Terminology:

Last

Form around which a shoe is typically designed and made

Upper

Part of the shoe that goes over the top of the foot

Outsole

Lowest layer of the sole that is in contact with the ground

Midsole

Layer of the sole that interfaces with the outsole and insole, often used to provide additional support and structure. Not a part of every shoe design, but is typically found in sports shoes.

Insole

Upper most layer of the sole, located inside the upper. Typically used for cushioning and directly supporting the foot.

Image Credits

All images and text are by the author, unless otherwise stated. The work was produced for the Master of Architecture Thesis at the MIT School of Architecture and Planning.

The exceptions for images are as follows:

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Video stills from the following videos, in order of top to bottom:

Insider, How Luxury Wallpaper Is Made | The Making Of - YouTube, accessed May 2, 2022, https://www.youtube.com/watch?t=130&v=ToksgxuSHnw&feature=youtu.be&ab_channel=Insider.

Avlyn Fabrics, Printed Fabric Production, 2013, https://www.youtube.com/watch?v=zuR2x0lorLg&feature=youtu.be&ab_channel=AvlynFabrics.

Insider, How The New York Times Is Made | The Making Of, 2019, https://www.youtube.com/watch?v=MrWP2z8I0Qk.

Indian YouTuber, Industrial Embroidery Process I Textile Factory Tour I Garment Industry Production Process Apparels, 2021, https://www.youtube.com/watch?v=xO7iY4Vx6PI.

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Graphic from Habib, “What Is Shore Hardness Scale?” https://plasticranger.com/what-is-shore-hardness-scale/

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Image of Dual Drive Extruder is from “Dual Drive Geared Extruder - RepRap,” accessed May 19, 2022, https://reprap.org/wiki/Dual_drive_geared_extruder.

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Image from Carolo, “ABS Acetone Smoothing.” https://all3dp.com/2/abs-acetone-smoothing-3d-print-vapor-smoothing/

Page 23 – 26:

All images are stills from video done in collaboration with Ziyan Zhang

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Third image from top is a still from a video done in collaboration with Ziyan Zhang

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Appendix

Appendix 1: Additional Notes on TPU

Moisture

One major challenge of working with TPU that I would like to take note of, is its susceptibility to absorbing moisture.[64] Whilst this is not a significant issue with the printed TPU object, it can disrupt the printing process itself. If the moisture content of the filament is sufficiently high, it may cause bubbling as the filament is heated up. At best, this can degrade the print quality and affect the adhesion of the extruded filament. At its worst, however, the bubbling can cause enough of a blockage in the hotend to cause clogs and jams. In this project, I managed the drying of the filament with desiccants and low heat (~140F / 60C) from a food dehydrator. Filaments were typically also stored in vacuum bags, or in sealed containers when printing.

Use of Cleaning Filament

I have often found it necessary to purge the hotend and nozzle when changing filaments after using TPU. This is best done with a sacrificial cleaning filament that is designed to adhere to any stray filament in the hotend.

Leaving the TPU in a heated hotend for too long without any extrusion can also cause clogging issues, but may be resolved with the cleaning filament as well.

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Appendix 2: Summary of Software and Hardware Used with Case Studies

Modeling:
Mostly done with Rhino 7 and Grasshopper

Slicing software:
SuperSlicer, a fork of the open-source Prusa Slicer, was used for the level of control it afforded over nearly every aspect of the slicing. [65]

From this software, G-code was generated in two flavors, Prusa G-code[66] for the Prusa MK3S+ and Klipper for the Voron 2.4 and roll-to-roll printer. The specific type of G-code is not as consequential, save for having enough functionality to 1) pause the print process to load the substrate 2) move the print head in the paused mode - to allow for enough room to manipulate the substrate.

That said, in the experimentation process, the extended G-code of Klipper[67] was particularly useful. This allowed for on the fly adjustment of print speed and filament flow to more quickly find settings that worked for a particular filament, or to rectify errors.

Print management software:
In a design process that involved multiple experiments, and consequently, repeated failures, I found it particularly useful to operate the 3D printers via printer management software. The printers were attached to Raspberry Pi's running either Octoprint[68] or Fluiddpi[69] , and served to store and execute GCode, but also allow for remote operation and video recording. The recordings, in particular, were crucial in identifying the specifics of print failures and learning from them.

Hardware:
All of the work done in this thesis was executed on one of two 3D printers, a Prusa MK3S+ and a Voron 2.4.

The Prusa MK3S+ is a kit printer developed by Prusa Research[70], and is representative of the type of FFF printer available to the public in retail. The printer has a Direct Drive setup with adjustable filament tension that allows for reliable printing with TPU. Its main drawbacks, however, have been its limited print bed size, as well as its Cartesian, "slinger" kinematics. Essentially, this means that the print bed moves on the Y-axis, something that proves challenging when trying to secure a piece of fabric to it.

The Voron 2.4 is an open-source design by the Voron Design group that features high speed CoreXY kinematics and a stationary print bed. The DIY nature of this printer means that there are many variables in its capabilities, electronics, and operating software, and perhaps represents a hobbyist setup - somewhere between a kit printer and a commercial production printer. The Voron's modularity has proved instrumental in experimenting with different filaments and print settings. Notable upgrades have included a dual-drive extruder and a "high-flow" hotend assembly.

Appendix 3: Specifications for Proposed 3D Printer Design

Moniker:
BBP, or BigBoi Printer

Kinematics:
Cartesian

Actuators:
X: Twin Belt and Pinion linear actuators, 1500mm, 3GT, 3mm Pitch, OpenBuilds[71]
Y: Belt and Pinion, 500mm, 3GT, 3mm Pitch, OpenBuilds
Z: TR8 lead screw, 150mm stroke, 2mm lead, generic
Connectors: Universal Plate, OpenBuilds

Motors:
X: 2 NEMA23 Stepper Motors, 3GT 20T Pulley, Openbuilds
Y: NEMA23 Stepper Motor, 3GT 20T Pulley, Openbuilds
Z: NEMA11 Stepper Motor, generic

Endstops:
X and Y: Hall effect, contactless endstop, Voron Design[72]
Z: Microswitch endstop, generic or Voron Design

Extruder Assembly:
Extruder: LGX Dual-gear extruder with adjustable tension, Bondtech[73]
Hotend: Ultra-High flow Rapido, Phaetus[74]
Thermistor: Built-in, 104NT-4-R025H42G
Heater Cartridge: Built-in, ceramic
Inductive Sensor: TL-Q5MC2-Z NPN NC, Omron
Assembly Design and Parts: Voron Stealthburner, 3D printed from models by Voron Design
Part Cooling: 5010 Blower, 24V, generic
Hotend Cooling: 4010 Fan, 24V, generic

Alternate Extruder Assembly:
Extruder: LGX Dual-gear extruder, Bondtech
Hotend: Shortcut Copperhead, Bondtech

Electronics:
Printer MCU: BigTreeTech Octopus Pro
24V Power Supply: LRS200-24, Mean Well
5V Power Supply: RS25-5, Mean Well
Print Management: Raspberry Pi 4B

Stepper Drivers:
X and Y: Trinamic TMC5160 , BigTreeTech[75]
Z and Extruder: Trinamic TMC2209 , BigTreeTech

Software:

Firmware and G-code: Klipper
Web Server: Moonraker
GUI: Fluidd
BootOS: Fluiddpi, fork of Raspberry Pi OS Lite

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