DESIGNED DEPOSITION

Freeform 3D Printing for Digitally Crafted Artefacts

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ABSTRACT

Through the exploitation of new additive manufacturing (AM) processes, this research seeks to reinvent the designer as an informed mediator between the digitally defined and the physically expressed.

Current 3D printing techniques generally construct an object layer by layer, building vertically in the z-axis. Recently developed, 'freeform 3D printing' is an AM method which builds through the deposition of material that solidifies upon extrusion. The result is free-standing material forms with diminished need for support material.

Building in this spatial manner means that AM is no longer reliant on layer based techniques that are built from ground-up. Instead, motions can move simultaneously in the x, y and z axes. This increased freedom of motion allows the designer to disregard the requisite that solid forms need to be delineated prior to considering material deposition. Considering this in relationship to the design of artefacts, specific approaches that consider both form and material deposition concurrently allow the authorship of the method of making to be reclaimed.

Bespoke computational processes work to encode material deposition with qualities that are tactile, visual and expressive of its making method. Considerations to structural, performative and aesthetic implications are assimilated from the onset rather than post-rationalised. Material deposition is crafted to become three-dimensionally informed and considerate of the integral nature of its making method and its output, exposing new design opportunities.

Among other things, the research-through-design process suggests how parametric modelling could be used for mass-customisation and suggests a possible path for AM beyond prototyping, towards the manufacturing of bespoke products through an industrial design perspective.

Through iterative abstract and application based experiments, Designed Deposition pursues an increasingly integrated process between the user, the designer, the digital and the physical, towards the creation of digitally crafted artefacts.

PREFACE

Knowledge as a tool.

"It is not craft as 'handcraft' that defines contemporary craftsmanship: It is craft as knowledge that empowers a maker to take charge of technology."
-Dormer, 1997, p.140

A tool for digital craft.

"Through combining the precision and flexibility of tools of digital fabrication with the visual quality and tactility brought by the tools of craftsmanship, the modern artisan is empowered to take the best of both worlds and create a new one, and with it – introduce a new kind of marker's mark."
-Johnston, 2015, p.10

A digital craft translated by machines into the physical - for the individual or the mass scale.

"By the machine we mean an instrument of mass production. In a sense, every tool is a machine – the hammer, the axe, and the chisel. And every machine is a tool... The problem is to decide whether the objects of machine production can possess the essential qualities of art."
-Read, 1934, p.3-4

ACKNOWLEDGMENTS

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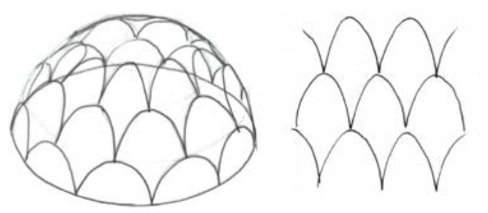


Figure 1. Author, Common 'banding' or 'space-frame' methods used by many freeform precedents

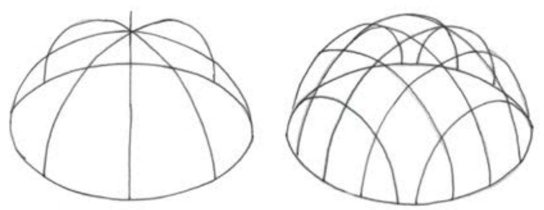


Figure 2. Author, Simple example of proposed 'Form Responsive Method'

INTRODUCTION

Freeform 3D printing provides opportunistic capacity for new approaches to building additive 3D forms. Currently, one of the main types of additive manufacturing (AM) is fused deposition modelling (FDM). This method melts and extrudes filaments of printing material, most commonly thermoplastics through a fine print nozzle and deposits thin layers of material that build up to form 3D geometries. Freeform 3D printing retains parent novelties from FDM printing, using the same computer numerical control (CNC) machine capabilities in conjunction with material extrusion to build 3D forms. No longer relying on planar layering techniques. Instead, it employs self-supporting build material that solidifies upon extrusion to create free-standing material strands in space. These are generated from the toolpath of the CNC machine which exploits the freedom of simultaneous x, y and z axes movements. Through this process, the need for support material diminishes. Resourcefully designed, the path the print head follows can become increasingly economic in material use and printer movements, as well as reduce post-print clean-up.

Current applications of freeform 3D printing are dominantly proto-architectural. These projects often look at large-scale building solutions for complex structures, taking a structural space-frame approach in creating three-dimensional printed forms (Figure 1). These defined by automated dispersing algorithms become reflective of the traditional slicing processes, building ground-up. This research endeavours to take intended forms and structures into consideration from the onset, informing bespoke material deposition differentiating the process from any automated, banded or layering methods.

Figure 2 illustrates the form responsive method (FRM), which fully utilises simultaneous x, y and z axes movements with regards to the intended form. FRM disregards the requisite that solid forms need to be delineated prior to considering material deposition. Instead, artefact specific approaches will be used to consider both form and material deposition concurrently. Artefacts are now fundamentally defined by repetitious lines used to create a toolpath which determines the geometries of three-dimensional built form.

Evolution beyond traditional layering or common banding techniques allows for exploration of the new opportunities that come with gaining greater control over how material can be deposited. The FRM poses opportunity for embracing functional, aesthetic and tectonic applications of material, prospering upon the predominantly structural pursuits currently in the field. Through an industrial design perspective, this research will explore how this 'Designed Deposition' can develop extrusion based printing methods beyond rapid prototyping.

CNC technologies with both 3 and 6-axis of motion present unique benefits and hindrances as a tool for spatial printing methods. While most research to date is conducted through the use of robotic arms with 6-axis of movement, by comparison, this research uses standard 3-axis FDM printers. The capability of CNC machinery for custom creation separates it from the homogeneity of mass manufacturing (Bak, 2003). Through the use of generative processes, user customisation is viable. Users could be allowed the opportunity to adjust defined aspects of artefacts on a broad and locally oblivious scale, such as with Nike ID (Nike, n.d.). Through parametric modelling, user customisation capabilities are explored in the creation of bespoke AM products.

This research pursues an amalgamated process between the user, the designer, the digital and the physical, exploring"...capacities of new tools and techniques to emancipate form, liberate structure, and energise the material..." (Leach, Turnbull and Williams, 2004, p.142)

TERMINOLOGY

3D printing:

The process of making a physical object from a three-dimensional digital model through additive accumulation of material. Typically by laying down thin layers of a material in succession.

Additive Manufacturing (AM):

Used interchangeably with 3D printing, AM is a physical object created from building materials additively, as opposed to subtractively taking away from stock material.

Rapid Prototyping:

Within AM, Rapid prototyping describes the use of 3D printing technology to quickly fabricate a model or part.

Fused Deposition Modelling (FDM):

A common AM technique which 3D prototypes with thermoplastics and other materials. Extruded as a semi-molten filament, the material is deposited on a layer-by-layer basis to construct the prototype from 3D CAD data.

XYZ Motions / Axis:

XYZ refers to points, motions, or axis using three dimensional Cartesian coordinate system. For 3D geometry, the standard orientation of these refer to the x axis as width, y as depth, and z as height. Motions of a CNC device run though co-ordinates defined by x, y, and z axis positions.

Computer Aided Design(CAD):

The use of computer systems to aid in the creation, modification, analysis, or optimisation of a design. In this instance, the chosen CAD software is Rhinoceros 3D.

Computer Aided Manufacturing(CAM):

The use of computer software to control machine tools for manufacturing. The CAM technology here is the 3D printers; Makerbot Replicator 2X and MendelMax.

Computer Numerical Control(CNC):

The automation of machine tools employing computers to execute pre-programmed sequences of machine control commands. The CNC devices used are the two aforementioned 3-axis desktop 3D printers.

Parametric / Generative Design and Modelling:

Parametric design is an algorithm based process that enables the expression of parameters and rules that, together define, encode and clarify a relationship between design intent and design response. Parametric and generative modelling are software with platforms for the creation of manipulatable digital models and outputs. The used parametric software in this research is Grasshopper, which is supported by Rhinoceros 3D

Toolpath:

The path through space that the tooling tip of a CNC machine follows to produce the desired geometry of an artefact. In this research, this is delineated first by a single digital line, which is translated into a text based code (g-code) of CNC positioning information.

G-Code:

G-code is the name for a text based numerical control programming language, mainly used to control automated machine tools. It is used in this research predominantly for control of the motion and extrusion instructions of a 3D printer.

Example G-Code:

Start codes;

```
M190 S100 ; set bed temperature
M104 S235 ; set temperature
M109 S235 ; wait for temperature to be reached
G28 ; home all axes
G1 Z5 F5000 ; lift nozzle
G21 ; set units to millimeters
G90 ; use absolute coordinates
M83 ; use relative distances for extrusion
G92 E0
...
```

Main text body defining print speed, material extrusion rate, and positional coordinates;

```
...
G1 F1000 E2.71 X70.52 Y45.78 Z0.55
G1 F1000 E1.47 X70.52 Y52.18 Z0.55
G1 F1000 E14.4 X70.52 Y114.78 Z0.55
G1 F1000 E0.74 X70.52 Y118 Z0.55
G1 F1000 E2.27 X70.71 Y127.87 Z0.55
G1 F1000 E1.78 X71.14 Y135.62 Z0.55
G1 F1000 E2.1 X71.98 Y144.71 Z0.55
G1 F1000 E2.5 X73.35 Y155.48 Z0.55
G1 F1000 E5.33 X77.24 Y178.32 Z0.55
...
```

End codes;

```
G1 Z50 F1000 ; lower z axis
M104 S0 ; turn off temperature
M84     ; disable motors
```

PROJECT SPECIFIC AND SELF-DEFINED TERMINOLOGY

Freeform 3D Printing / Freeform Printing:

An extrusion based printing method utilising self-supporting build material that solidifies upon extrusion during spatial movements.

Spatial Printing:

Used interchangeably with freeform 3D printing, but encompasses any printing that utilises simultaneous axis movements and less specific to self-supporting materials.

Material Deposition:

The act of material being extruded or deposited. The main factors towards control of material deposition are extrusion rate, printer speed, and material placement.

Designed Deposition:

Designed and informed control over how and where material is deposited with consideration to the aesthetic, physical and structural implications on the intended artefact. This, as opposed to geometrically oblivious automated slicers or material dispersing systems.

Form Responsive Method (FRM):

Material dispersion that in some form references or is impacted by the intended geometries of an artefact.

QUALITY TERMINOLOGY

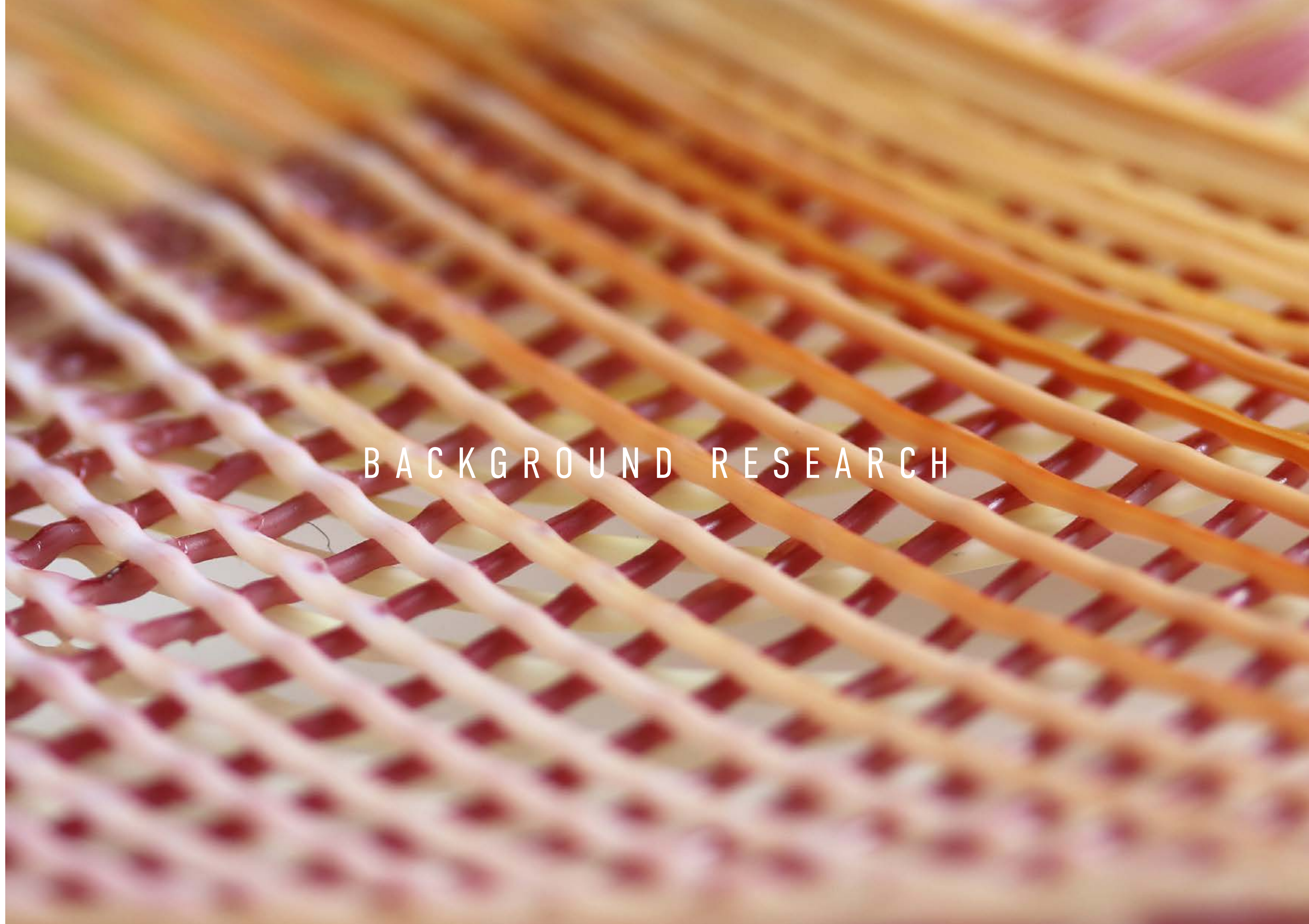
Craft / Digital Craft

Craft is known as a skill, art, or dexterity for doing or making something. Pye expresses that craftsmanship is inclusive of "workman using any kind of technique and apparatus, in which the quality is not predetermined, but depends on the judgement, dexterity and care which the maker exercises as he works." (1968, p.20) Technology is now embraced as an aid for the workman. In digitally crafting materials both the designer and the machine can become the maker.

Tectonics / Digital Tectonics

Tectonic in general is denotion or relation to construction or making. Movements, expressions or results of forces conditions and actions. Digital tectonics becomes the physical expression of actions that have defined through digital mediums. In 3D printing, the tectonics are the printed qualities denoted by motions, speeds and extrusion rates. Creating visual, tactile and textural expressions of the making process.

PART 1



BACKGROUND RESEARCH

1.1 - LITERATURE AND PRECEDENT REVIEW

ANALYSIS OF EXSISTING PRINTING TECHNIQUES

Materials, machinery and software are largely consistent throughout current precedents. However, with varying focuses towards the use of the technology, the articulation of the freeform printing method is diverse. They range from being strikingly experimental in their use of materials, making, and computational utility, to being heavily application, construction or technically focused.

Freeform 3D printing has mostly identical physical requirements to FDM printing; a CNC device and an extrusion tool. So, while it doesn't require many further advances in AM's physical technology itself, it does require a revised and open-minded consideration to how we approach 3D printing as a manufacturing method. The spatial freedom removes the security of layer based methods that can take nearly any geometry and make it printable through upward growth, allowing the process to be customised and uniquely considered in relation to desired qualities.

Research of the triumphs, holdbacks and implications of existing projects and precedents become vital to gain an understanding of the field. In the realm of a new method of making, technical information is momentous towards obtaining a knowledge basis build from. As imposed by Dormer, this knowledge creates empowerment for the maker to take charge of technology (1997, p.140).

In-depth research was undergone into current freeform techniques and findings. From this information, a matrix was developed to further understand unique, comparative, and discrepant factors of a representative sample of spatial printing projects. Included are projects which were closely aligned with the research pursuits at the time of investigation (July 2016 - May 2017). The matrix illustrates an overview of these findings, seen in full in Appendix A, with a visual reference seen in Figure 3. All projects in this analytical matrix use simultaneous x, y and z axes movements and extruded material.

The upper categories explore settings, materials, and other technical information available towards their achievements. These will be constructively considered during similar technical setups of the computational and practical development stage. The remaining categories of the matrix are collated information in regards to all relevant theoretical, contextual, and general findings or implications, which are discussed in the literature review and throughout the thesis. Less specific projects in further reaching contexts were also researched and subsequently included within analysis and discussions.

Researched Categories

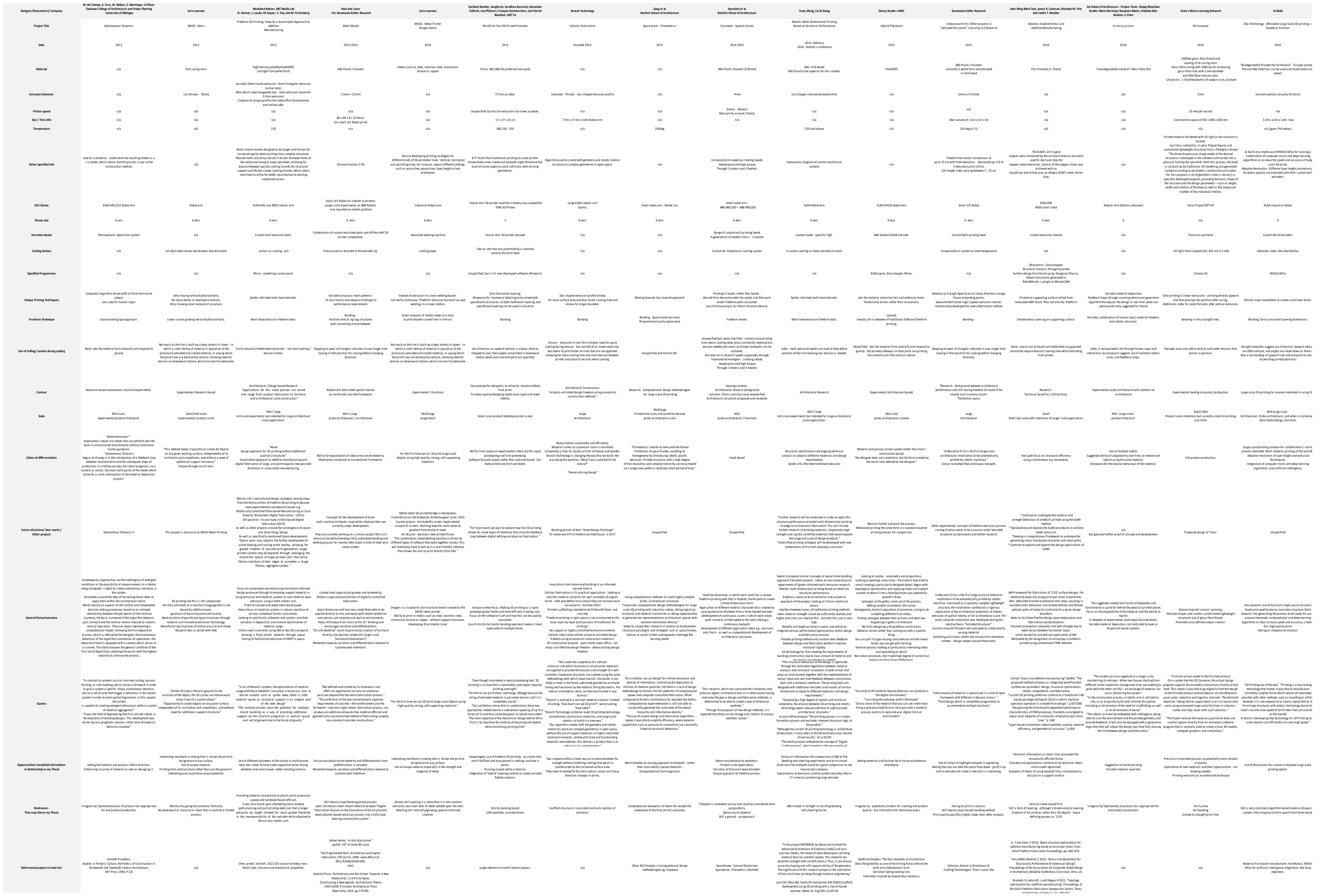


Figure 3. Author, Precedent Research Matrix Visual Reference

MATRIX INFORMATION OVERVIEW

Although disclosing varying levels of information about process, settings and theories in the precedent projects, value and information were gained from all. General summaries of each section indicate an overview of how each factor of freeform printing was considered by the representative sample. These will be discussed in greater depth throughout the literature and precedent review.

Material	*Extrusion Diameter*	*Printer speed*	*Size / Time Info*	*Temperature*	*Other Specified Info*	*CNC Device*	*Device axis*	*Extrusion device*	*Cooling devices*
-Most common is ABS, especially performance based project rather than experimental -PLA and HDPE used on few occasions, mostly for more experimental projects -Laarman (2012, 2014) also used resin and metal	-Often unspecified but most appear below 4mm - Thickest extrusion achieved by Branch Technology (n.d.) through star extrusion profile - A small number of multi-strand endeavours	- Curvoxels (2014-2015) the only project to specify - speed was increased over research by developing extrusion technology	- Mostly unspecified - Sizing dependant on CNC device	- All that specified are using ABS with heat range of 210-240 -Other assumptions are; -HDPE much lower -Metal extremely high heat -Resin no heat for extrusion	- All info unique, often technical knowledge	- All but two robot arm devices, both large and small - And when aiming for large scale construction, they were mounted on a moveable base - Wireprint the only project using standard 3D printer (Mueller et al., 2014)	- All but two using 6-axis	- Most custom made extruders based on generic 3D Printer extrusion nozzles -A small number of creating multi-head extrusion nozzles	- Cooling blower/ compressor systems in most unless unspecified -Most using multiple pipes directed at the beginning of extrusion. -Metal no cooling -Glass fibre using light instead - Resin appears to use heat to help to cure

Specified Programmes	*Unique Printing Techniques*	*Freeform Technique*	*Use of Pulling/ tension*	*Context*	*Scale*	*Claims of differen-tiation*	*Future directions/ later works*	*Opportunities + beneficial info*	*Hindrances to note*
- All specified used a Grasshopper/ Rhinoceros 3D - Tam et al., of Robotics-enabled stress line additive manufacturing specified other programmes of note (2016)	- Unique per project	- Dominated by varying types of spaceframe or banding approaches, especially when structural / output / architecturally based - Experimental projects offered more diversity in processes. - Others had structural focus', so prints were more research than output focused	- Most output focused projects used tension by dwelling at the apex of a triangular form. - More experimental projects often allowed drooping and used tension less	- Dominantly proto-architectural, but also experimental usually with architectural backgrounds/ contexts. - Some technically / material research focused - few touch on industrial design applications but more structurally considered	- Mainly Mid/large - Mid - mainly proto-architectural Large - for more applied/application focused architectural contexts -A handful of small-scale outputs or pursuits, such as Wireprint for rapid prototyping (Mueller et al., 2014)	Unique - But often adhere to one of multiple of: - Material/process driven - Technical Research / Optimization - Nature informed / Sustainability - For novel architectural construction method - Computational complexity	- Mainly specific technical improvements	- Proof of concept through successful projects - Technical information and guidance for successful settings/ strategies - Increased cooling time through thin extrusion, or increased surface area -Conceptual guidance from research based projects - embracing imperfections and letting material drive the designs, technically driven or structurally focused - Use of colour for increased toolpath readability	- Often statements/ claims/ideas exceed outcomes and cheats/ exaggeration of ability is seen - ABS strength criticised to be limited in shearing/ bending forces - Size / geometric restrictions resulting in printing in sections -Inconsistencies in material deposition in research-based projects, but more unique use of toolpath -Outcome based projects lack material and structural variability

TECHNICAL FACTORS INFOGRAPHIC

While the general findings from the Precedent Matrix (Appendix A) will be discussed further throughout the thesis, the technical, contextual and printing methods that help to inform the research direction and printing approach were further analysed in an infographic to help visually understand common and discrepant factors amongst the precedence. (A Visual reference is seen in Figure 5, for full format see Appendix B)

Many technical settings were not directly specified, but often guided guesses could be made from available information or visual cues from images or videos. The infographic shows this through a lessened transparency of the images, to indicate the factors not certain, or not specifically stated, but those that are an informed judgment to help understand overall trends.

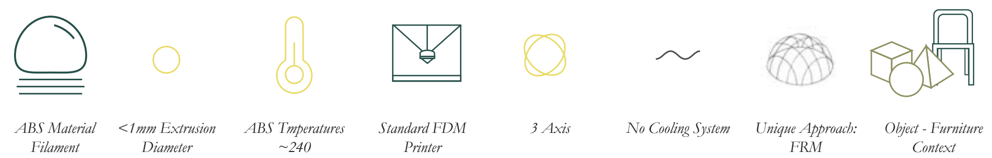


Figure 4. Author, Peronsal Research Technical Factors Infographic (Visual Reference)

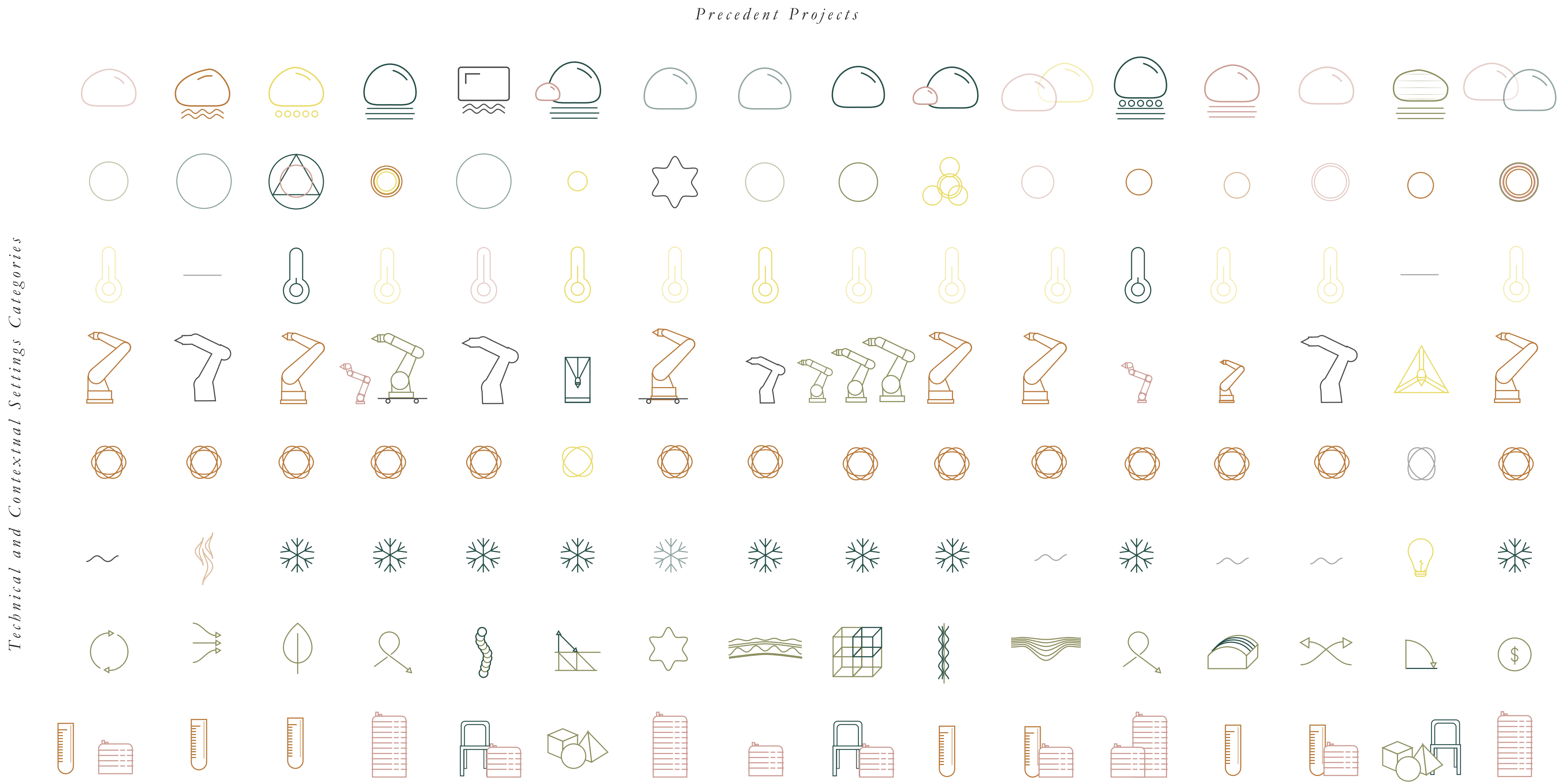


Figure 5. Author, Precedent Technical factors Inforgraphic (Visual Reference)

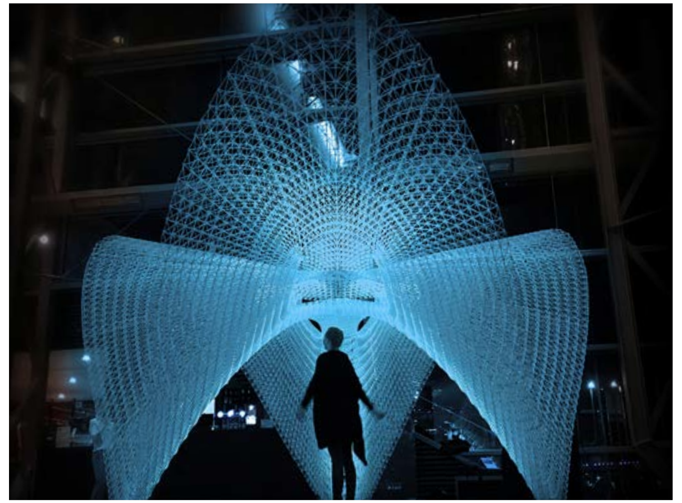


Figure 6. 3Dp Technology - Affordable Large Scale 3D printing, Daedalus Pavilion. (Ai Build, 2016)

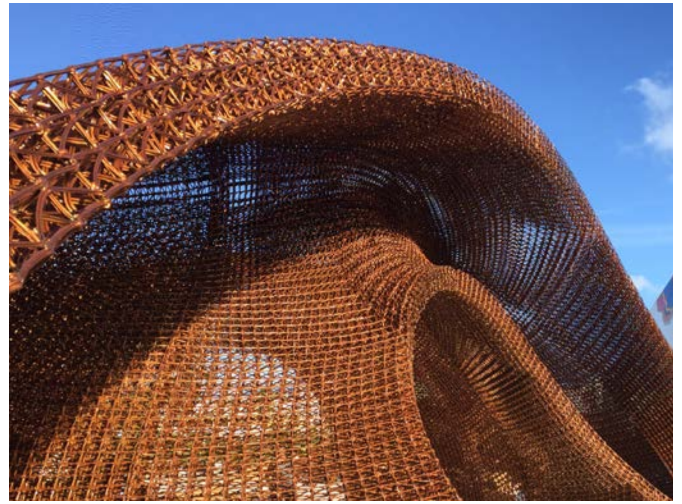


Figure 7. Flotsam & Jetsam Pavilions (Branch Technology & SHoP Architects, n.d.)

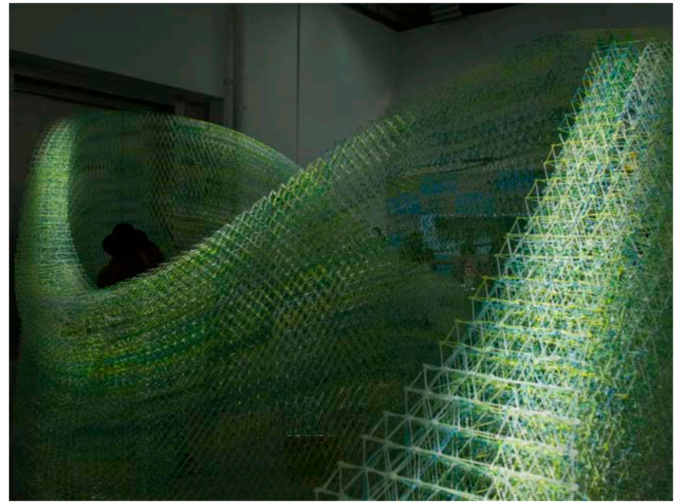


Figure 8. Iridescence Print (Gramazio Kohler Research & ETH Zurich, 2015)

CONTEXT, APPLICATION, AND SCALE

Efforts are being made to develop the capabilities of additive manufacturing technologies for broader applications, scales, and contexts. Currently, common and accessible types of additive manufacturing (Fused Deposition Modelling, Stereolithography, Selective Laser Sintering) are produced on a relatively limited scale, for primarily prototypical or one-off creations (Bak, 2003). Micro and Macro applications of AM are emerging, and freeform 3D printing is finding popularity towards novel large-scale applications. Precedents of freeform printing being dominantly proto-architectural in their approach, many researchers in this field look at large scale building solutions for complex structures, such as Ai Build (2016) Branch Technology (n.d.) & Gramazio Kohler Research (2015 & 2012-2016). Most of these have been constructed through a structural space-frame strategy, exporing at how materials can be dispersed in large, uniform constructs, to create lightweight but stable structures, with architectural scale intent (such as seen in Figure 6, Figure 7 & Figure 8). These and other projects manage to surpass the usual desktop scale exclusive of direct intent due to their use of non-specific equipment. Freeform printing is now finding traction in the larger scale 3D-printing realm, as variations of robotic arms are not limited to a specific platform size as off the shelf 3D Printers are.

As a whole, there are three primary underlying contexts and applications of which the projects adhere within one or multiple of;

- Experimental projects, taking a more abstract, materially or theoretically driven approach to the process

- Technically focused projects that research thoroughly a structural or efficiency based motive with use of 3D extrusion and movements

- Output or production focused projects that have a desired purpose or artefact as the driver of the process, such as the architectural outputs seen in Figure 6, 7 & 8

As the freeform process is directly expressive of the toolpath that the printer follows, the digital design of the process and toolpath is as important as the act of printing itself. Throughout the precedents there are varying degrees of emphasis on this computation complexity. Some projects provide heavier weight and research towards the computational development and the construction of this toolpath digitally, while other projects direct focus more towards the expression of the physical process and resulting outputs.

Overall, most of the projects can be considered within architectural or proto-architectural contexts. Therefore, it seems prudent to investigate freeform 3D printing on a reduced, design-centred scale. New possibilities may be expedient through integrated inspiration of the experimental, technical, and output discoveries exposed in existing research.

FACTORS TOWARDS SUCCESSFUL DESIGNS BY ORDER OF IMPORTANCE

Figure 9. Author, ID Factors Ordered

1.
Function
Aesthetics

2.
Cost
Maintenance

3.
Environment
Ergonomics
Materials
Customer specification
Company Identity
Fashion
Culture
Prestige Value
Assembly/Disassembly

4.
Economic Viability
Form
Conformance
Durability
Reliability
Performance
Customization
Style
Industrial Production
Usability
Tactility

CONTRIBUTING FACTORS ARRANGED INTO RELATED CONCEPTS

Figure 10. Author, ID factors Collated

AESTHETICS
Materials
Fashion
Form
Style
Tactility

FUNCTION
Environment
Ergonomics
Customer specification
Materials
Usability
Assembly/Disassembly
Maintenance
Durability
Reliability
Performance

VALUE/ECONOMIC VIABILITY
Cost
Materials
Industrial Production
Prestige Value
Assembly/Disassembly/Maintenance

OTHER
Company Identity
Culture
Conformance
Customization

ADDITIVE MANUFACTURING and INDUSTRIAL DESIGN

Industrial Design (ID) is the professional service of creating and developing concepts and specifications that optimize the function, value and appearance of products and systems for the mutual benefit of both user and manufacturer.
- Industrial Design Society of America (IDSA), 2016

Industrial design has been defined by the Industrial Design Society of America (IDSA) to seek the benefit of both the user and the manufacturer (2016). In the case of the manufacturing method at hand, AM, the printer becomes the manufacturer itself. The device and process has needs, requirement, limitations, and preferences. A rich understanding of the manufacturing method allows the designer to become an informed mediator between user and manufacturing method. The language between these, in this case, is g-code, informed by primarily toolpath, extrusions settings and speeds.

Ordinarily, the delineation of these is through automated slicing systems. While these slicing systems keep the manufacturing method comfortable, they can impede design qualities such as textures, quality and materiality, giving the appearance of low-fidelity outputs. In 1968, Pye made observations about the uniformity of mass manufacturing;

> *The failure of mass production is not that it is incapable of producing quality products, but that it has created a system of undifferentiated, uniform, and characterless products; a material culture which gives little value to workmanship and craft, and the potential of both. (p.need to find again)*

Parallels can be drawn between this statement and the creation of toolpath and print information for AM, particularly in FDM or similar methods. Using indifferent slicing systems and approaches to create objects with unique requirements is guarding the ability to consider the material quality of products, and holding it within a prototypical realm. Increasingly high-resolution printers are providing capacity for the creation of 3D printed final products, such as for one-off complex pieces (Bak, 2003). Reclaiming the authorship of material through informed curation of its deposition could pose an alternate path for developing the process beyond rapid prototyping. This creates opportunities for a conversational relationship between user needs, product requirements, and the printing process to be of value towards user, product and manufacturer.

A modest analysis was developed comparing factors considered to be of greatest value towards successful design.

Four sources (Norman, 2016, Ryan, 2005-2009, Martin, 2014 & Soni, 2015) were analysed and their information collated into a hierarchy of factors from the most to least recurrent elements, as seen in Figure 9. They were subsequently collated by the author into groups with related concepts (Figure 10), which became reflective of the design values stated in the industrial design definition by the IDSA in 2016. These factors were researched to inform the development and iteration of product focused designs. Providing specific factors for material deposition to respond to when being designed.

A small portion of freeform precedents suggest uses of this technology with reference to industrial and product design motives. Wireprint uses a standard FDM printer and its software breaks the input form into a wireframe mesh that is spatially printed. The creation of this for low-fidelity wireframe printed previews in the early stages of the design process, allowing for quick and iterative design processes. (Mueller et al. 2014, p. 273) While the project is within the product scale and context, it doesn't seek to use the process for a final product purpose, but rather make AM possible to be an even faster rapid prototyping system. Hyunchul et al's project Curvoxels (2014-2015) also exemplified outputs within an industrial design context, recreating the Pantone chair through a voxel-based printing method. They produced unique and variable computational methods which allow for different densities of material dispersion depend on local needs of the chair, but were primarily from an architectural standpoint, with focus on structures and forms. With the identification of this industrial design perspective towards the use of material deposition for the benefit of the product, user and manufacturing method being ill-explored, this research seeks to find the merits of spatial printing for bespoke industrial design-centred products, with response to the researched influencing factors.

Figure 11. Autonomous Tectonics - a Research into Emergent Robotic Construction Methods. (Del Campo, Fure, McGee, Manninger, and Flexer, n.d.)

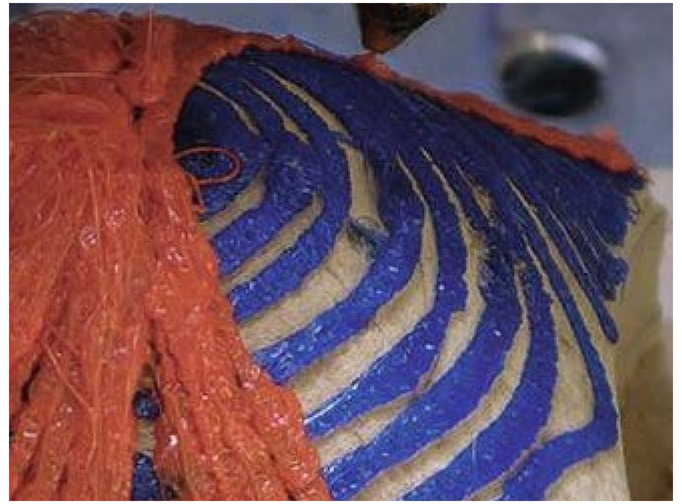


Figure 12. Robotics-enabled stress line additive manufacturing. (Tam, Coleman, Fine, & Mueller, 2016)

Figure 13. Dragon Bench. (Joris Laarman Lab, 2014)

PRINTING AND STRUCTURAL APPROACHES

The premise of freeform 3D printing seeks to develop beyond strictly layer-based methods that build up in 2D planes in the z-direction. While all freeform printing precedents incorporate simultaneous x, y and z axes movements, many still build geometries using a ground-up system. As touched on previously, these spatial forms are often built up in 'bands' of spatially printed areas and layered up vertically (as seen in Figure 1). Projects such as those by Mueller et al. (2014), Ai Build (2016) Branch Technology (n.d.) & Gramazio Kohler Research (2015 & 2012-2016) use a very distinct banding approach as their process towards breaking up large geometries into layers of spatially printable bands. The benefit of this is, as in traditionally 3D printing, almost all geometries can be run through a slicing system, and turned into printable information.

Arguably, the projects using this printing approach have the more successful prints due to the fact that the geometries are directly comparable to the intended digital models, with little material distortion or impact from outside factors such as gravitational force. In reflection of this, these projects are more output based than experimental as they focus on creating structurally sound objects or constructs that reflect a desired form or surface structure with a performative purpose.

While the aforementioned projects all use 3D bands that build up cumulatively, other projects use a similar approach but start to let the toolpath and material deposition have more response to the geometries at hand or the requirements of the objects. The Spacewires project (Jiang et al. 2014) also uses a banding like technique but the shape of these bands begin to take influence from the overall form of the object rather than being cut through an XY plane. Their project is heavily focused on computational complexity, and this more complex and variable 'slicing' or geometry forming software makes for more diverse structural qualities. Curvoxels, (Hyunchul et al. 2014-2015) researched the use of 'spatial voxels' as a tactic for breaking up geometries and printing them in voxel structures that build up like blocks. While this is again using planar slicing techniques and building ground up, the structures inside the voxels are varied in density and geometries to reflect the local structural needs of the object, once more through the development of complex computational methods as well as structural analysis.

The projects that have less focus on output and more on experimental research often look at particular aspects of the printing process and exploit or utilise them in various ways. Projects Hybrid Phantasm (Disney Design Studio et al. 2015), and Autonomous Tectonics (Del Campo et al., n.d.) let the material be the driver of the process and form responds to how the material reacts to outside influences, such as seen in Figure 11. Many of the more technically, structurally, and efficiency focused research projects look into how materials and freeform processes can be utilised to enhance the performative value of the object or materials, such as through multi-extrusion tools, such as in the projects Freeform 3D printing: Towards a sustainable approach to additive manufacturing (Oxman et al. 2013) and Robotic Multi-dimensional printing based on structural performance (Yuan et al. 2016). Other structurally focused research has been undergone through non-freeform, but spatially deposited material that varies due to being locally based and is on stress lines, as shown in Figure 12.

By taking into consideration the influential factors from the performative and materiality findings of these projects and combining them with the structural successes of the output focused projects, there is potential to create processes that maximise the opportunities that arise when designing a toolpath spatially as opposed to through layer based formats. The structures of Laarmans Dragon Bench begins to visually move the process away from layer-based tactics which can result in low-resolution qualities. By allowing form to influence structure with greater intricacy and consideration, (as seen in Figure 13), structure expands and contracts around form. Reflecting the intentions of the defined Form Responsive Method (Figure 2).

As discussed, the approach of many of the freeform precedents takes inspiration from slicing software like that of common 3D printing toolpath generators in which majority of motions take place in the X and Y axis. This research seeks to manoeuvre toolpath generation away from trying to be an all-encompassing printing process that can print any input geometry through a standardised process. It instead looks to utilise diverse tactics for Designed Deposition as an integrated approach between consumer, designer, computer and digital realisation.

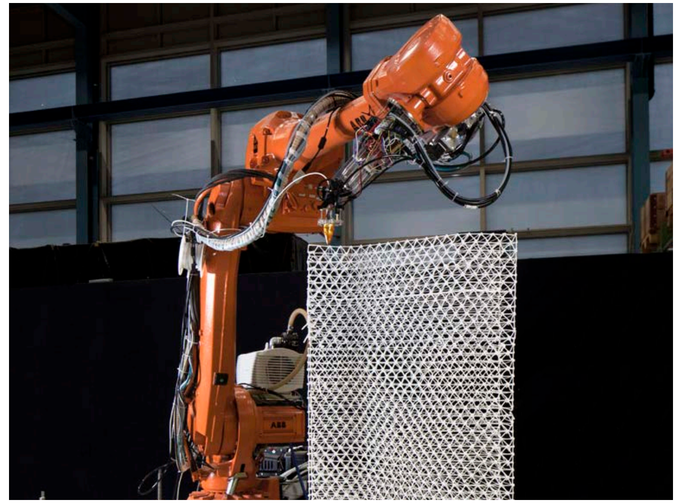


Figure 14. Mesh Mould. (Gramazio Kohler Research, ETH Zurich, 2012-2016)

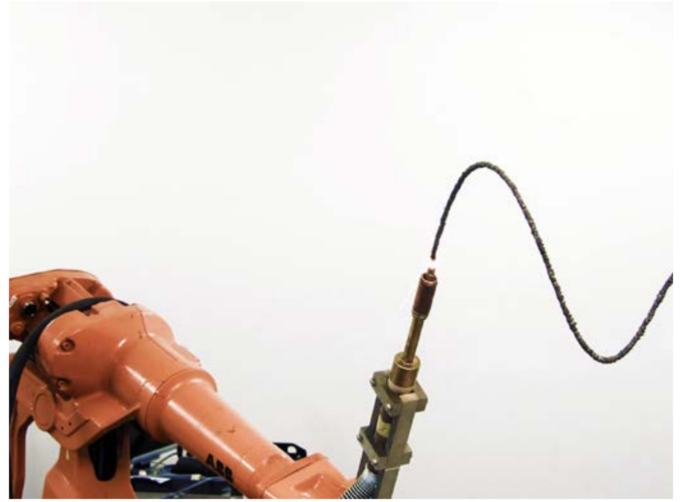


Figure 15. MX3D Metal during despoisiton. (Joris Laarman Lab, 2014)

ROBOTICS IN ARCHITECTURE AND DESIGN

“We should look carefully at how human action organises itself around machinery, how machinery organises and even institutionalises action, how it slowly takes away or enables freedom”
- Storebroek, 2011, p.27

It has been suggested that CNC technologies have greatly narrowed the gap between what is plausible in computer-aided design (CAD), and what is possible regarding materialisation and constructional limitations (Hack & Lauer, 2014, p. 46). Through additive manufacturing, 3-axis CNC capabilities and extrusion methods are used to create geometrically complex forms most commonly through layering methods. However, in circumstances where layering is not used, 3-axis can be limiting, as the tool head can collide into existing geometries if undercutting forms are delineated.

Most robotic arms have 6-axis of movement resulting in great dexterity. This exposes the ability to manoeuver around existing geometries and has a higher level of control over toolpaths and tool-head orientation. Robotic arms have been widely adopted in architectural research projects that look into new ways of fabricating complex structures. It becomes a powerful tool that can be customised for bespoke construction processes, simply by changing what tool is integrated onto the robotic arm (Budig, Lim, & Petrovic, 2014, p. 26). With an extruder attachment, a large-scale 3D printer is born.

For these reasons, nearly all of the precedents looked into were working with 6-axis robotic arms. The majority were using large ABB or KUKA models, such by Gramazio and Kohler Research, their large ABB arm seen in use in Figure 12. While 6-axis of motion has greater flexibility and control, there may be advantages in looking into and comparing the use of 3 axis CNC devices for freeform 3D printing. 3-axis devices such as regular 3D printers are easily available, and assembly between CNC device and tool-head is not needed as they are already integrated. 3D printers and other 3-axis CNC devices currently are more physically and financially accessible than their 6-axis counterpart, therefore requiring less training, supervision and technical knowledge. While the software or printing information if using an FDM printer needs customisation to be suitable for spatial printing, little physical manipulation or maintenance is required compared to that for integrating an extrusion method to a 6-axis robotic device. Syncing physical movements of these devices with extrusion rates and information requires substantial technical developments. Most freeform precedents develop in-house custom extrusion and cooling methods specific to the device, materials, and intentions of their project.

The dexterity of 6-axis machines is utilised surprising scarcely for governing the direction or angle at which material is extruded. Projects by the Joris Laarman lab, as seen in Figure 15, are the most dominant utilisation of this ability. With this, 3-axis and its inability to control extrusion direction seems to be only a minor hindrance. The restraints of lessened manoeuverability for collision avoidance could be considerably compensated for by well-considered toolpath creation and informed print tactics.

As aforementioned, the main benefits of 3-axis machinery are the inclusivity towards a wider range of users, and more easily accessible equipment. It allows for the use of a standard FDM printer to become a tool for spatial printing with minimal modification. With this, it is primarily a revised utilisation of machine control that allows for adoption of freefrom processes, rather than demanding the development of new technologies also.

This research intends to find the benefits and compare and limitations of freeform 3D printing through 3-axis CNC devices, already equipped with extrusion capabilities. The process takes influence from the synergy between software, hardware, and form that has arisen from the use of robotic arms as a tool for realisation when using computer aided design.

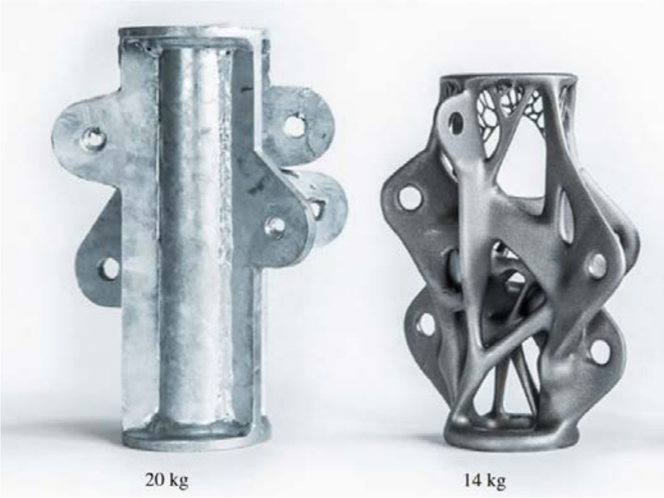


Figure 16. Topology optimisation and reduced waste, photographed by Davidfotografie (Galjaard, Hofman, Perry, Ren, 2015)

Figure 17. Fibrous Tectonics (Menges & Knippers, 2015)

STRUCTURES, TOOLPATH AND EFFICIENCY

A range of design research projects pursue efficient use of material. Often inspired by nature they seek to design a process of fabrication, rather than and outcome. The additive process of 3D printing finds itself appropriate for this nature inspired stance, with project such as Freeform 3D printing: Towards a sustainable approach to additive manufacturing (Oxman et al. 2013), Growing Systems (Bermejo, Matei, Bek-Bulatov & Chen 2016), and Cellular Fabrication (Branch Technology, n.d.) apply this ideation through spatial printing practices.

The standard form-structure-material design process for architecture and design has been criticised as resulting in post-rationalisation caused by a separation of design and engineered thinking. (Oxman & Oxman, 2010, p. 17).The use of CNC and robotics has been noted to begin the inversion of this process, to material-structure-form. (Oxman & Oxman, 2010; Oxman, N 2010;). This ability allows the designer to engage in the fabrication process from the onset resulting in greater consideration being given to material, thus structurally enhanced concepts. According to Oxman & Oxman meaning "There is now momentum for a revitalised involvement with resources and technologies" (2010, p. 15). Throug inspiration from nature, these projects have come to develop consistent ideals in terms of material deposition, particularly in nature's use of structural necessities as the driver of design. Placing material only where needed to perform the desired functions, compared to our previously subtractive ways of manufacturing, of which Neri Oxman describes as "much less effective, and mostly wasteful" (2010, p. 80). Galjaard, Hofman, Perry, Rens' Topology optimisation and reduced waste (2015) proved this technique successful in the realm of 3D printing (Figure 16). Using Finite Element Analysis (FEA) and defining local needs and parameters for form to 'grow' within.

> *Imitating this growing and adaptive process of biological structure allows for a design and modelling process that combines structure with geometry, material, function and manufacturing information to achieve the best performance through appropriate material distribution. (p. 36)*

Variability of material deposition provides an opportunity for control over the structural implications of its placement. Schumacher et al. (2015) at Disney Research investigated Microstructures to Control Elasticity in 3D Printing. These investigations provides precedent for AM with variable property design of a single material for not just variable placement of structural strength, but also tactile and responsive materiality, fabricating deformable objects with spatially varying elasticity. Location, direction, and density of material placement can be controlled to create broad opportunities for improving material qualities, such as researched by Menges and Knippers in Fibrous Tectonics, seen in Figure 17. Their research suggests that by orienting and locating each fibre individually in space across several layers of hierarchy we can begin to blur the boundary between material and structure, and thus "extends the scope of design towards the realm of 'designable' materiality." (2015. p. 46) Spatial and custom extrusion methods provide a promising platform to explore this process that Menges and Kipper propose and prove. The use of self-supporting materials diminishes the requirement of a support structure, allowing even more freedom over material placement, therefore creating variable and informed material and structural qualities.

Freeform precedents such as Curvoxels (Hyunchul et al. 2014-2015) and Robotics-Enabled Stress Line AM (Tam et al.2016) begin to invite this initiative into the field through variable density and stress line informed material deposition. Not only does this begin to use material deposition with greater consideration to structural needs, but also begins to provide interesting visual variation.

While this research is not engineer-based, nor does it focus on structural analysis, it does seek to use material deposition efficiently and effectively in relation to the structural, functional, visual and design requirements of objects. Material placement will be designed with influence from these research findings and ideas, as opposed to automated slicing or dispersing approaches. Spuybroek has discussed the invitation of structured to impress qualities of aesthetic interest into an artefact and vice-versa, stating "If ornament can accentuate structural form, structure itself can be seen to contribute to the ornamental." (p.65)

Figure 18. Filament Sculpture (Lia, 2014)

Figure 19. Topolabs Print (Page, 2014)

Figure 20. Vessel – Experimental G-Code (Lobser, n.d.)

DESIGNED MATERIALITY, TEXTURES AND TECTONICS

Some materials promise far more than others but only the workman can bring out what they promise.
-Pye, 1968, p.18

The freeform 3D printing process is transparent and explicit. Structure, materiality, and process are directly expressed through the toolpath that the print head follows, and the outcome visually articulates each movement that the printer had made. Through this, a conversational relationship between the digital and the physical can emerge.

In digitally defining each movement, we can translate this information to the physical world with greater consideration of the process of making. This brings a craft-like quality to digitally manufactured objects, reflective of the premise of the work collated by Lucy Johnston in Digital Handmade: Craftsmanship and the New Industrial Revolution (2015).

In designing the whole process rather than just form, the opportunity arises to encode material, not only with structural or functional material qualities, but also tectonic, visual, and expressive qualities that inform the product with an expression of its making. This allows for textural qualities to be explored with greater intricacy, beyond forms and surfaces, down to a material level. This provides an opportunity for a broadened and more three-dimensional informed consideration towards printed textures and tactility. The usually unwanted 'low resolution' or stair-stepping aesthetics and tactile trait that comes from print layers can instead be reconsidered and reformatted to become a design element. This greater homogeneity between the digital information and physical realisation means we can craft digital technology, such as in Lia's filament sculptures (Figure 18). Lia's series explores using a 3D printer as an artistic medium beyond layer based restrictions to create a "series of sculptures are discovered by exploring the parameter space of a base model" (Lia, 2014, para. 6). She controls the material to a certain level, but also lets its viscosity and cooling process be defined by gravity and other contextual forces to find unique and unrepeatable textures, forms and qualities. In an opposing, very controlled consideration to textures, tectonics and quality, Topolabs (2014) software by James Page brings in the use of simultaneous x, y and z-axis movements to enhance the final material quality and appearance of FDM prints. Printing an initial support structure in the traditional planar layering method of printing, the final print layers are subsequently layed down through fully three-dimensional toolpaths. While it's not purely freeform printing, it shows the advantage of material deposition that is three-dimensionally informed by the geometries of its artefact, seen in Figure 19. Peeters' Drooloop Flowers (2014) is a maker-culture example of how simple processes can be undergone to create variable printed tectonics that provides visual expression or function relative to the intended outcome. This project also highlights considerations regarding cooling time and toolpath, and how these can be exploited or controlled to create varying effects, visually, structurally and performativity. In this, the centre structure is printed by using a layered and consistent process for a sturdy stem-like structure. 'Petal' sections are printed with the fan off and with custom settings to result in more naturally formed and tectonically considered materiality. David Lobster is another artist using custom FDM processes to create unique materialities by experimenting with the effects of custom printing parameters in his Vessel series (n.d, seen in Figure 20). These projects begin to blur the linear hierarchy of first defining form and then structure and materiality being subsequently considered.

> *If you look at any surface-making, when you move into making structure off those surfaces you get into ornamentation and secondary values as well, so that you have a new territory of primary and secondary. (Leach, Turnbull & Williams, 2004, p.143)*

Extruded material deposition formed into geometries becomes reminiscent of strands of material fibres being crafted into textile fabrics. On these grounds, textiles provide vast inspiration for possible materialities, textures and tectonics that could be employed to freeform print toolpaths. Many textiles projects explore similar concepts to what is of interesting potential towards spatially printed designs. For example, Rita Parniczky's architectural inspired work that looks at explores the performance and movement of the vertical monofilament lines (in her X-Ray Vault Series III, No I)(2016), and projects from French studio Matières Ouvertes in their exploration of fibre based structures and variable densities (2013).

With inspiration from the qualities and knowledge found in aforementioned research and precedents, there is opportunity to discover how material deposition can be further crafted and encoded with structure, tactility, visual interest and materiality with greater consideration than that possible of current banal layering systems.

The workmanship of the motor car is something to marvel at, but a street full of parked cars is jejune and depressing; as if the same short tune of clear unmodulated notes were being endlessly repeated. A harbour full of fishing boats is another matter. Why do we accept this as inevitable? We made it so we can unmake it. Unless workmanship comes to be understood and appreciates as the art is, our environment will lose much of the quality it still retains.
- Pye, 1968, p.2-3

ADDITIVE MANUFACTURING for USER AND MASS CUSTOMISATION

3D printing and CNC technologies allow the possibility to industrially manufacture individual non-standardised elements (Gramazio, Kohler, & Oesterle, 2010). With these technologies there is no incentive or benefit in manufacturing duplicate objects as there is when tooling and moulding are involved, thus, it becomes appropriate for consumer customisation services. This has been implemented by (Rosenkrantz & Louis-Rosenberg, n.d.) through generative modelling and an online customisation service. Beyond AM, mass customisation has been implemented with proven success, most notably by Nike, through their service Nike Id (n.d.). In fact, Nike Id was originally only meant to be a marketing campaign, but its user input tapped into the interest of the consumer and "through the exploitation of technological developments, rapidly became a major strategic asset to Nike" (Angioni, Cabiddu, & Di Guardo, 2012).

In 2003, Bak recognised that the application of additive manufacturing is inherently linked with rapid prototyping, and anticipated a merge of these capabilities with the high-volume production of conventional manufacturing (p. 340). This was described as rapid manufacturing, refering to the delivery of finished goods directly from digital data, leading to tool-less production and the mass-production of individually customised goods. It is advocated that for rapid manufacturing to infiltrate new markets more effectively, some changes need to occur. Namely, machinery needs to become less expensive to buy, maintain, and use, as well as being developed to support the creation of end product fabrication, rather than at prototypical quality. (Wohlers, 2003, as cited by Bak, 2003, p. 340) This development towards end-use or end product fabrication is emerging, with technologies for Additive manufacturing methods increasing in complexity, accuracy and many other aspects. Further growth is foreseen, as identified in a report published in Stratasys Direct Manufacturing Trend Forecast (2015), with note that this "expanded adoption of 3D printing for end-use parts does not happen in the blink of an eye—it happens one application at a time"(p. 25). In mass, it seems that realisation towards this goal will be found through high-resolution parts, with minimal visibility of print lines. Freeform 3D printing could offer a new path in searching of this end-use goal. In celebrating the manufacturing process, material deposition and toolpath, we can exploit the spatial method and exposed printed tectonics to be of benefit to the end-use of a product.

Rapid production of additively manufacture objects in terms of production economics encompass several cost advantages; lesser waste than subtractive processes, input material is consistent, meaning no inventory of a variety of standard-sized stock is necessary, reduced labour for fabrication and assembly, and better quality control as production is digitally driven thus less room for human error as well as minimal setup costs (Bak,2003, p. 341).

Spatial printing processes allow some of these values improved further, such as in the vast reduction of waste material, therefore requiring less post-print clean-up. Although still in its early research stages, with development there may be potential for a unique path towards end-use additively manufactured products through freeform 3D printing methods, enhanced through the integration of mass customisation and rapid production.

New platforms are being developed to help accommodate this notion. MatterMachine (n.d) is an online node-based parametric modelling programme, seeking to play part in the democratisation of manufacturing. The programme is made for ease of both designer and consumer with platform for easy adjustment of inputs, and output of manufacturing data. Programmes such as this show value in how generative platforms can begin to integrate mass customisation and rapid production motives that include the consumer as part of the design process.

Grasshopper is well established with vast resources and plugins to aid the creation of complex models and information. For these reasons, Grasshopper is used as the parametric platform for this project, but the web-based structures provide promising platforms for bringing mass customisation methods to be realised in future.

OVERVIEW AND INTENTIONS

A multitude of precedents are discovering impressive qualities, possibilities and applications for spatial printing methods. Through the use of 6-axis robotic arms, the process has been exemplified for the creation of complex architectural geometries with real world application. Experimental freeform projects and the maker community have started to digress beyond traditional layer based printing techniques and begun to experiment with how more variability in settings and material deposition can be used to enrich visual and tectonic qualities. Structural and technical pursuits express value towards more informed and economic dispersion of material.

By amalgamating these concepts and successes, one could begin to understand the value of this technique in the spaces between the micro and macro, the tinker and the engineer. An industrial design perspective provides a new set of guidelines and proprieties to interpret the process through. This provides a context to develop artefacts with curated materialities for the integration of output focused, tectonically considered and structurally informed freeform printing.

Traditional slicers of AM and the material dispersion systems seen in many freeform precedents hold value in their ability to take almost any 3D geometry and make it printable through upward growth. This research however, seeks to use freeform printing to create printed artefacts through bespoke deposition and computation processes. For which, it is endeavoured to disregard current assumptions that printed geometry must first be defined as a solid form, to subsequently be turned into manufacturable information. Instead, to create artefacts that explore diverse and unique sets of print tactics as opposed to algorithm based layers or spaceframes. Through this, the research aims to investigate the opportunities of Designed Deposition through freeform printing.

By refreshing the way we approach digital technologies, with respect and response to the needs of the product, its user and the manufacturing method, opportunity is exposed to embrace a revitalised relationship between the designer and the digital. New methods will be developed and explored with the intention of creating objects for applications beyond prototypical use, working towards product based outputs.

Exploration of user customisation will be integrated through the use of parametric modelling. The research seeks to find techniques that allow material dispersion to respond to elements of form, aesthetics, structure and function, as well as how users could be providing input and controlling parameters of how these factors are actualised.

Standard FDM printers will be adapted as tools for this project. This use of 3-axis machinery will be explored in comparison to the large body of research completed through 6-axis robotic arms within the field. Understanding of the printing language and process becomes paramount to creating the desired integration between the computational and the physical spaces. Focusing on this inclusive and concurrent conversation between designer, user, and technology, it aims to prosper upon expedient print factors to discover new opportunities for materiality from an industrial design perspective.

> *When we make, instead of predetermined action, we discover a map of engagement. We play by challenging and resisting material. It, in turn, reveals an unintentional resistance that provokes another challenge, and on and on. In fact, craft excels in the less than ideal situations. When challenged by aberrant materials, geometry and craft are forced onto innovative discovery. (Harrop, 2004, p.1)*

TAKING A LINE FOR A WALK

In pursuit of the outlined motives, including bespoke and responsive design of deposition, a revised outlook on how deposition is delineated is endeavoured. Instead of first digitally defining a solid form (as is standard for 3D printing), it is now to be defined directly by lines or curves, to become the printer's motions, or toolpath. This toolpath, as the path through space that the printer's extrusion tip follows, results directly in the printed geometry. To inform the printer of one continuous path to follow, a single digital curve will be digitally delineated.

Paul Klee's phrase, 'Taking a line for a walk', has been reinterpreted through poetry, music, and other artistic mediums, including within design as an armchair of the same name. (Häberli, Take a Line For a Walk, armchair, 2002). This expression is here interpreted through a digital 3D path. We can now take the printer for a walk, starting at the beginning of the toolpath, to be released when the line ends. The printed artefact becomes a visual expression of the taken path, exposing a new view on the relationship between a digital path, and physical motion.

MATERIAL

Printing material is a large factor contributing to the successful implementation of AM processes for end-product production. New extrusion-based materials are being rapidly developed and this is a vast area for research and development in its own right. The 2017 3D Printing Materials Conference noted that it seems that hardly a day goes by without new materials being added to the 3D printing palette. They express the importance that these materials hold towards further success of 3D printed products.

> *The roads to success in the 3D printing sector will depend on fine-tuning materials to the needs of each application. This fine-tuning process will involve the type and the quality, strength and costs of materials, but also the selection of marketing channels and for example packaging of the end product. (3D Printing Materials Conference, 2017, home page)*

While material is a major contributing factor for AM to develop beyond rapid prototyping, the vast possibilities and research needed finds it outside of the scope of this research. Here, focus is primarily on crafting the deposition and placement of material, rather than the development of the material itself. ABS, as the most common and proven successful available filament through the precedents, will be used for this research. While all outputs will be created with a single material filament, their implementation as final products would rely on the development of appropriate materials for specific outputs. Not only for physical and structural traits, but also the ability to print spatially and self-support.

1.2 - METHODOLOGY

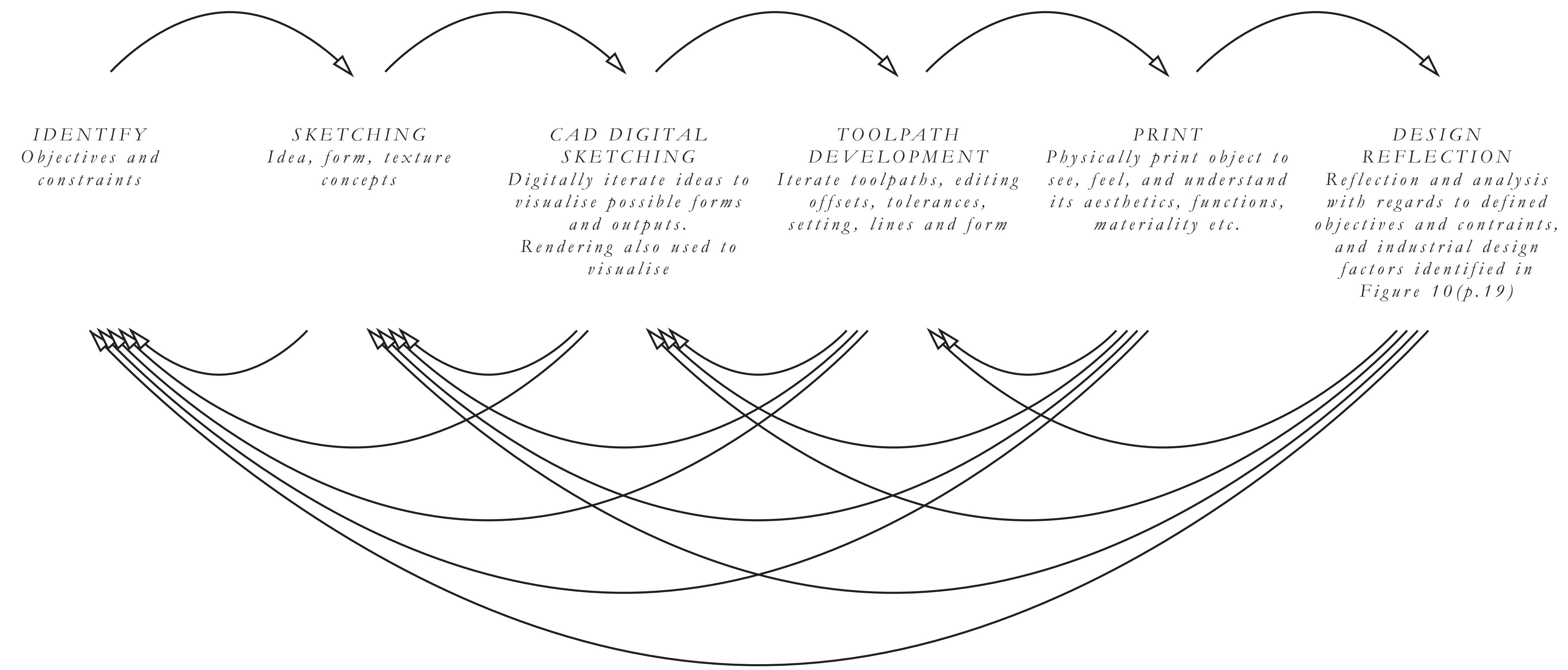


Figure 21. Author, Iterative Design Process

METHODOLOGY / DESIGN PROCESS / AIMS AND OBJECTIVES

Aim 1: Investigate possible design opportunities and appropriate areas of potential for spatial 3D printing techniques.

With the objective to identify current technical and theoretical approaches related to spatial AM and material deposition, exemplary literature and projects that hold relevance to this research were discovered, explored, analysed and discussed to gain a depth of knowledge within this field. This literature and precedent review, informed by such methods from Martin & Hanington (2012) and Cresswell (2013), developed necessary comprehension of the existing state of the field and aiding the discovery of possible opportunities within the scope of the research. The realm of this spatial AM technique is relatively recent in its advent, leaving many technical aspects still in development. Artefact analysis such as described by Martin and Hanington (2003, p.14) is an opportunity to systematically examine the material, aesthetic and interactive qualities to help understand existing contexts and implications. This premise was integrated into the precedent and research matrix (Figure 3), and specific technical information was further interpreted that helped inform a greater understanding of how outputs were created and their many implications (p.24-27).

As a whole, this matrix was developed in order to understand and to build platforms of knowledge gained from these projects, extracted from a variety of research pursuits. This comes from the influence of tactics suggested by Eilouti (2009) in design knowledge recycling using precedent-based analysis and synthesis models. Eilouti's emphasis is on recycling and building upon existing knowledge to inform future works. This process begins with raw data being extracted from precedents' documentation, achieved by undertaking thorough background research matrix (Figure 3, p.12), as well as supplimentary research that was undertaken. This is then to be reinterpreted and transformed into useful information. Subsequently, this information is structured and organised into developed abstract models of knowledge, discovered in the information collated through pages 24-27, and throughout the subject discussions.

Aim 2: To investigate, explore and exemplify design potentials of spatial printing techniques with informed material deposition from an industrial design perspective.

It is presented by Godin and Zahedi (2014) that there are three main forms of design research; research for design, research into design, and research for design. Due to the iterative, physically explorative, and applied intent of the research, a research through design methodology is utilised for subsequent work such as those described by Frankel & Racine, 2010, Martin & Hanington, 2012, and Milton & Rodgers, 2013. Fankel and Racine suggest that "in this approach, the emphasis is on the research objective of creating design knowledge, not the project solution" (2010, p.6). Towards this design knowledge, the objective to conduct material and form experiments and determine strengths and limits of the process is pursued. Preliminary tests to define appropriate print settings and physical necessities are undergone with relationship to technical and material information. These digitally defined and pre-extrusion aspects are then to be tested in terms of deposition in abstract experiments, in order to discover the implications of geometries and the process of laying down materials, with varying unique intentions.

Represented in Figure 21 is a structure of the design process that is utilised for the development artefacts, both experimental and application-based. The CAD/CAM realm is where the process finds itself heavily situated. Various computational strategies, both static and parametric, will be used to develop forms and structures. The step between digitally defining lines intended for material to be deposited, and organising these to become one printable and continuous toolpath takes a great deal of time and care. Therefore, various visualisation tools such as rendering are used to get the overall design form and idea developed to a suitable resolution. Frankel and Racine (2010) suggest that the most important aspect of research through design is that it seeks to provide an explanation or theory within a broader context. The objective of this research is to investigate opportunities towards informed use of spatial material deposition from an industrial design perspective. Requirements and aspects leading towards this criteria were defined in the small analysis in Figure 10 (p.19). These are to be used as design constraints, to be responded to during design development and iteration.

PART 2

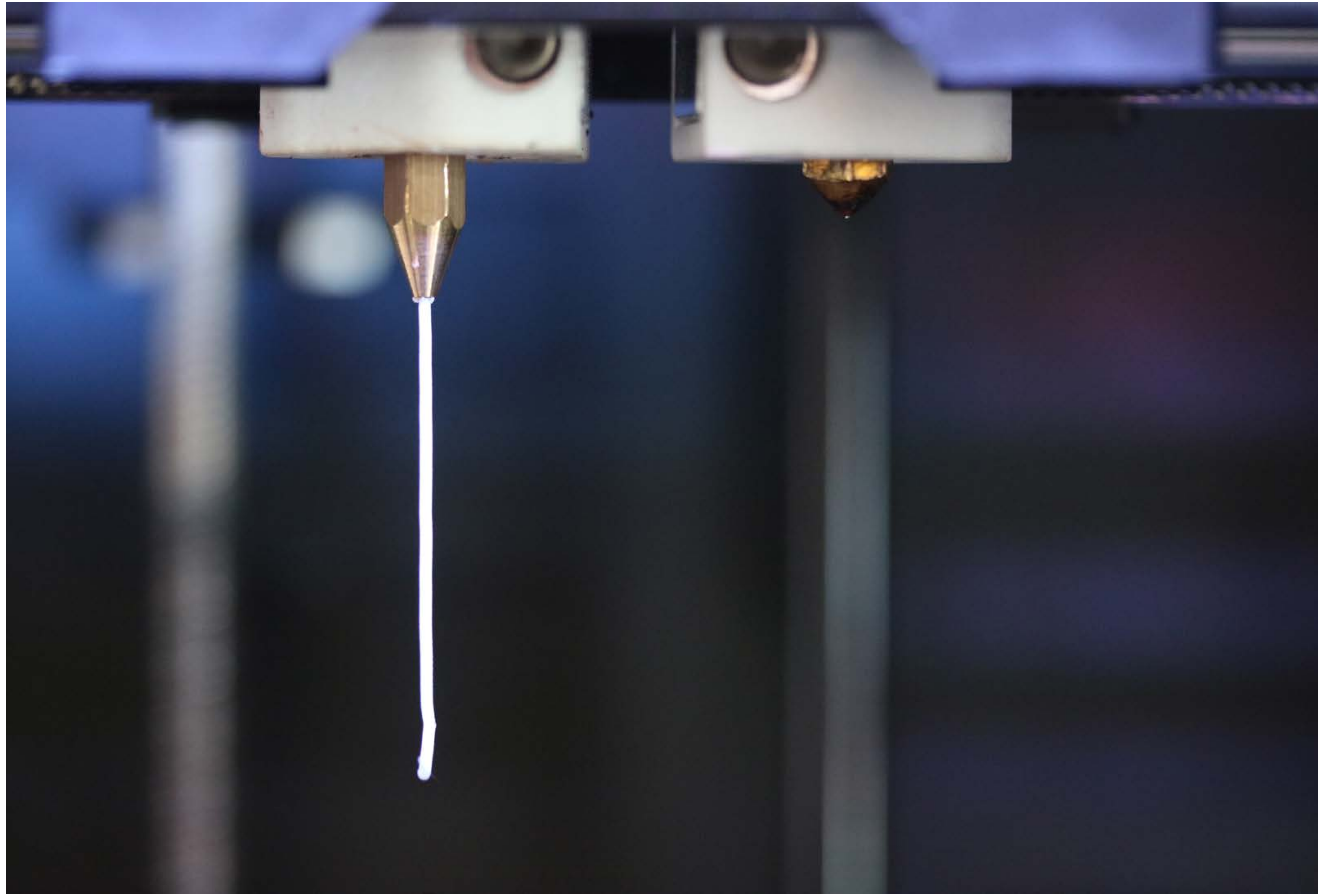


Figure 22. Author, Makerbot Extruder Head

2.1 - MACHINE ADAPTATION, COMPUTATIONAL DEVELOPMENT AND SETTINGS TESTS: MAKERBOT

Standard FDM printers provide the required technologies for freeform printing. CNC capabilities and an extrusion system. However, some adaptations and developments were undergone to maximise the printers ability to work spatially and to gain control over the printers motions and material deposition. Towards this, the following was undergone;

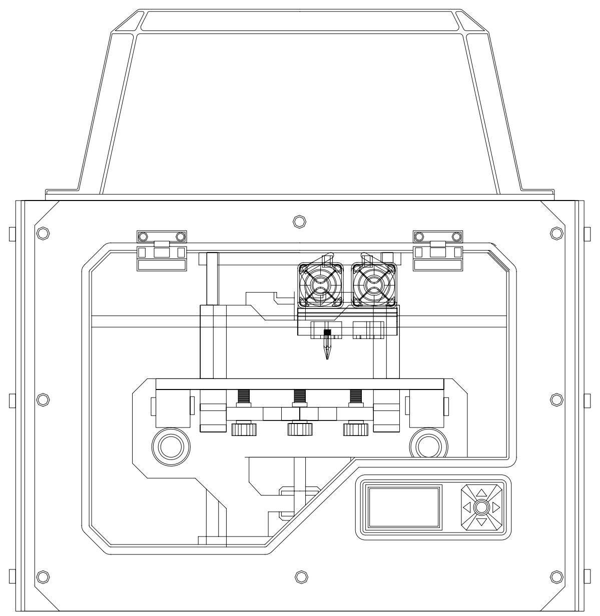
- Gaining an intimate understanding of the printer both physically and in software or coded requirements.

- Producing custom nozzles that are more appropriate to the freeform process and allow for increased spatial freedom.

- Creating custom computational processes that create G-code from an input curve/toolpath.

- Running a testing phase to create relationships between toolpath geometries and printing information.

MACHINE ADAPTATION - MAKERBOT REPLICATOR 2X

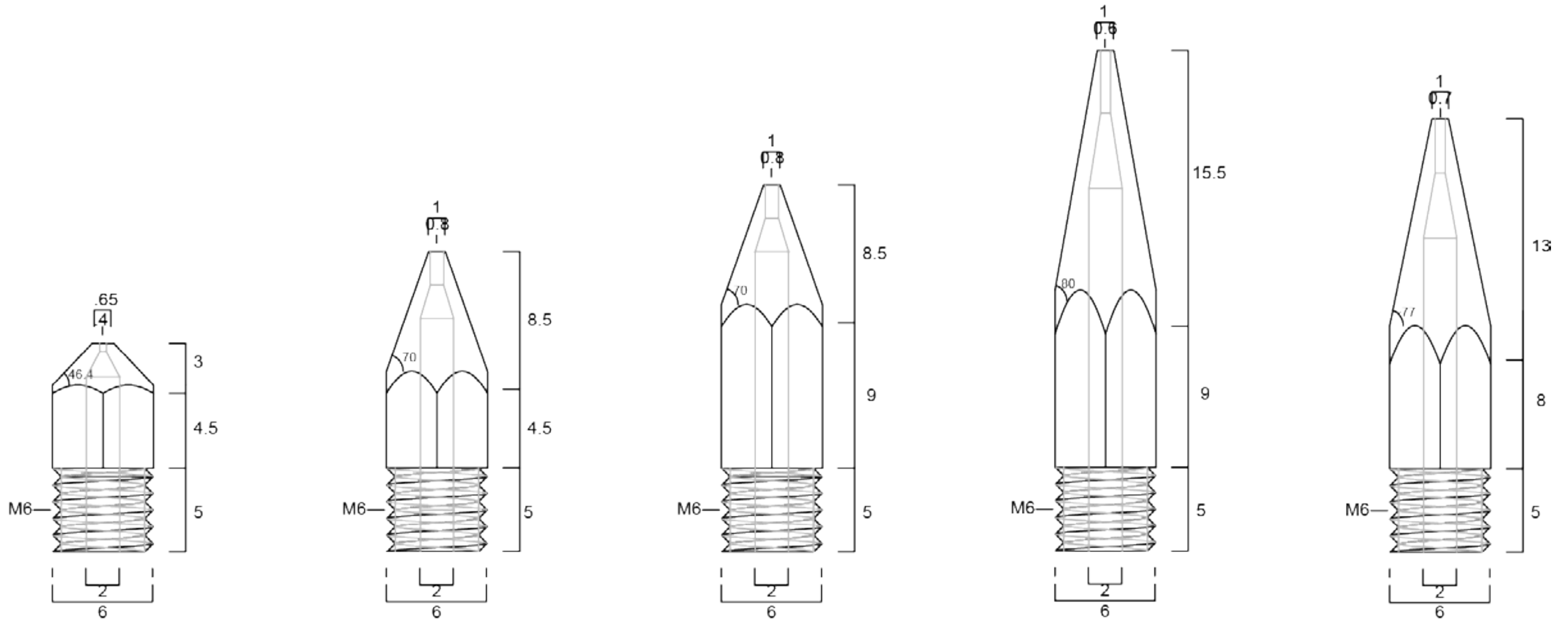


Makerbot Replicator 2X

Figure 23. Author, Makerbot Illustration

A Makerbot Replicator 2X is the device used during the experimentation phase, part 1. This FDM 3D printer allowed for user input g-code, as opposed to some other 3D printers that only allow the input of solid .stl files that a local slicing software generates the printing information for. Some minor adaptations were made to help improve the machine's ability to print spatially. Towards this, an in-depth understanding of the printer and how to maintain and update it was pursued.

NOZZLE ADAPTATION



Original Nozzle (N0) Nozzle 1 (N1) Nozzle 2 (N2) Nozzle 3 (N3) Nozzle 4 (N4)

Figure 24. Author, Nozzles 0-4

A range of new nozzles was developed specifically for spatial printing. The Original Nozzles' (N0) extrusion diameter and overall dimensions are small, as optimised for standard layer based FDM printing. Freeform printing called for adjustments in these dimensions, thus new nozzle iterations were developed and tested over the duration of the research (N1, N2, N3, N4, seen in Figure 24). Each time a new nozzle was integrated the extrusion settings had to be adjusted accordingly.

Nozzles 2 and 3 (N2 and N3) are tested in this section, 2.1.

Nozzles 3 and 4 (N2 and N3) appear later, in 3.1.

MAKING OF CUSTOM NOZZLES

Below: Figure 25. (a-d) Author, Nozzle Creation

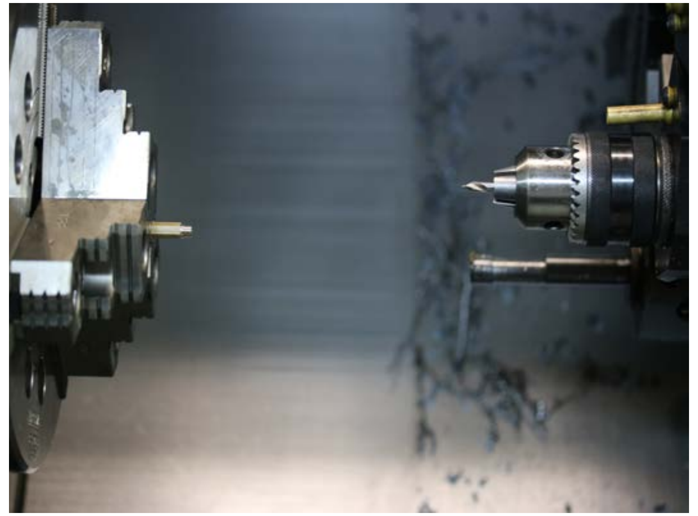


Figure 25(a)

Figure 25(b)

Figure 25(c)

Figure 25(d)

CNC Haas Lathe for creation for M6 thread and 2mm hole for 1.75mm filament to run through seen in Figure 25(a) and 23(b)

Manual lathe used to create custom nozzle taper, nozzle lengths and end extrusion hole diameter, seen in Figure 25(c) and 23(d)

PRINT BED OFFSET FOR NEW NOZZLES

Below: Figure 26. (a-d) Author, Bed Offset

Figure 26(a)

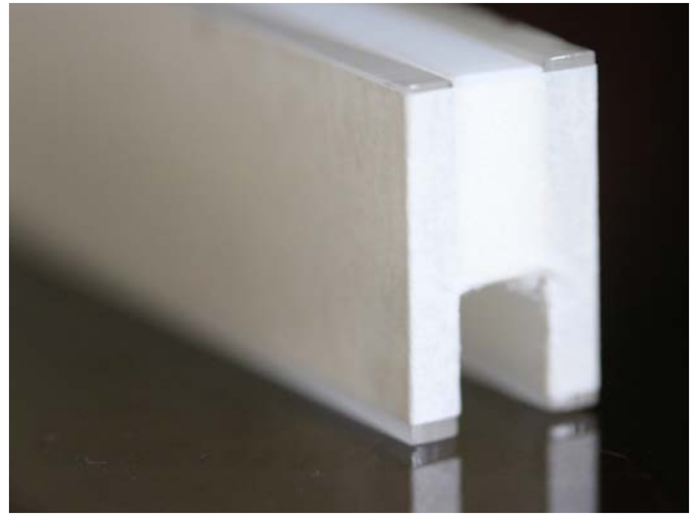


Figure 26(b)

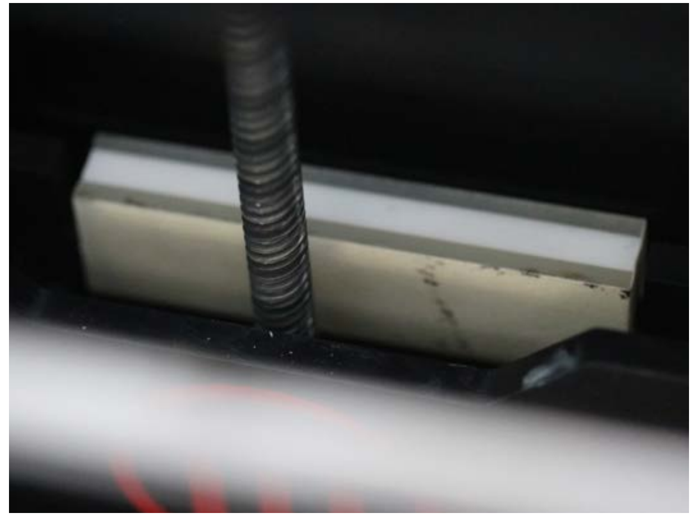


Figure 26(c)

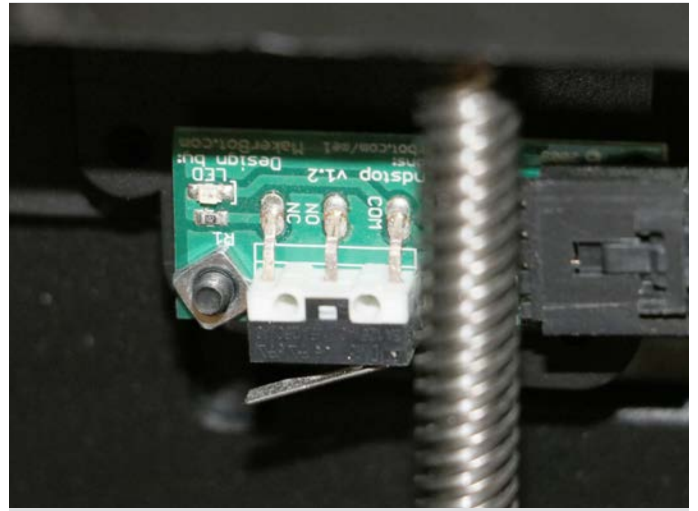


Figure 26(d)

As the new nozzles were developed with increased length, the Z-axis sensor needed to be offset to account for this. Otherwise, the nozzle would hit the bed before the sensor was triggered.

The difference between the new and original nozzle was determined, as seen in Figure 26(a), and a simple brace then made to add this extra dimension, seen in Figure 26(b)

This brace is then placed onto the area that triggers the end-stops, as in Figure 26(c), end-stop seen in Figure 26(d), so that the sensor is hit before the nozzle reaches the bed.

IMPLEMENTING NEW NOZZLES & EXTRUSION MAINTENANCE

Below: Figure 27. (a-l) Author, Extruder Head Disassembly

1. Remove filament

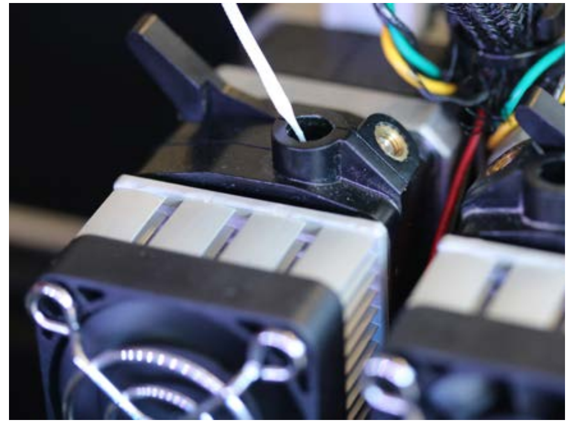


Figure 27(a)

2. Release both screws from Fan

Figure 27(b)

3. Remove fan assembly

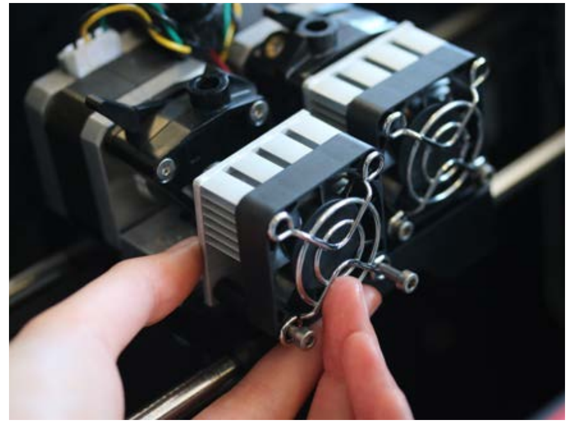


Figure 27(c)

7. Unscrew connection from extrusion brace

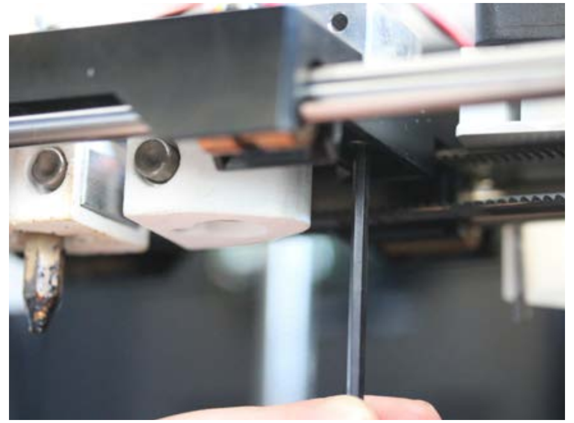


Figure 27(g)

8. Remove brace for access to nozzles

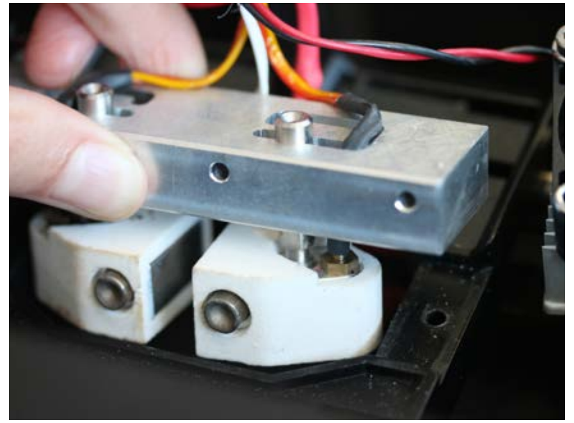


Figure 27(h)

9. Release screw holding the heater

Figure 27(i)

Taking apart the extruder head equipment became required for var reasons, both general maintenance and freeform specific adjustments.

The main reason was to replace the existing nozzle with the new, custom nozzles. This required almost the whole extrusion equipment to be disassembled, as demonstrated below in Figure 27 (a-l).

4. Unplug wire connection

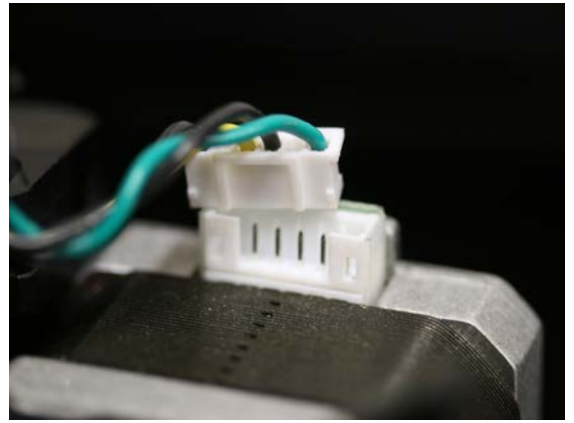


Figure 27(d)

5. Remove extrusion assembly

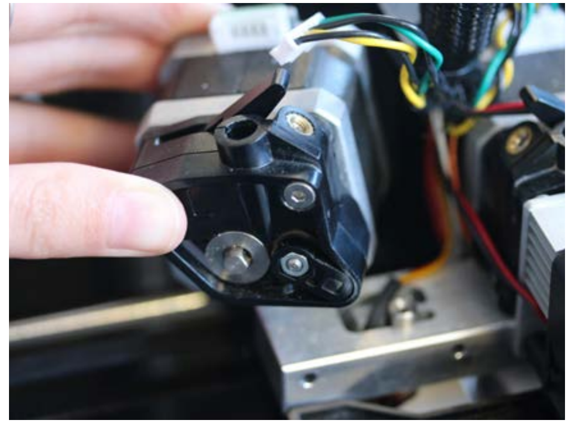


Figure 27(e)

6. Repeat other side so the metal brace is exposed

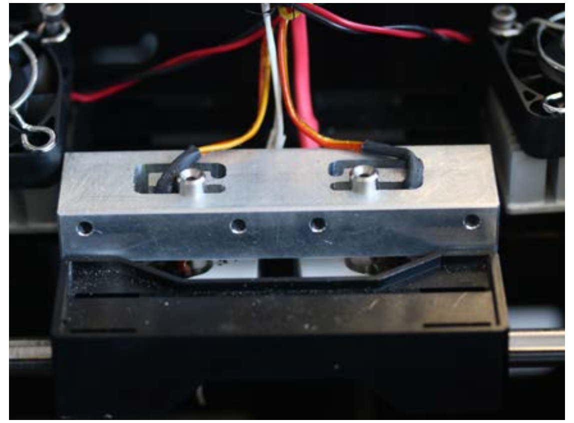


Figure 27(f)

10. Remove heater

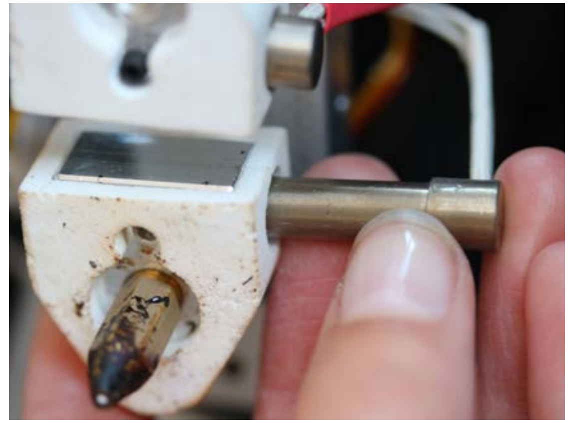


Figure 27(j)

11. Place strong object in heater cavity for resistance. Unscrew nozzle

Figure 27(k)

12. Replcae with new nozzle and put extrusion system back together.

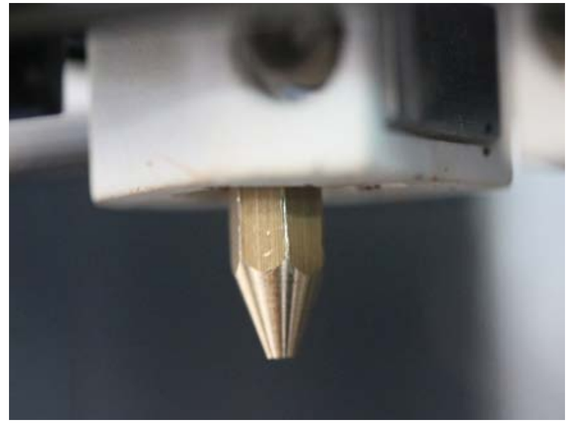


Figure 27(l)

COMPUTATIONAL AND SOFTWARE DEVELOPMENT

A largely important part of any 3D printing process is the software or printing information generator. "In fact, more than 90% of experts agree that 3D printing software has the greatest impact on print quality, even more so than the 3D printer itself" (Simplify 3D/home, 2015, para. 2)

As previously noted, toolpaths were to now be self-defined as opposed to created by automated slicing systems. Once a digital toolpath had been defined, this needed to be turned into printing information; points, motions, extrusion rates and speeds.

Scripts to achieve this were developed using generative modelling programmes; Rhino, Grasshopper and Silkwork. Silkworm is a plugin that translates Grasshopper and Rhinoceros 3D geometry into GCode for 3d printing. Allowing for the complete and intuitive manipulation of the printer G-code. (Silkworm/About, n.d.)

Through this system almost all digital manipulation, both toolpath and manufacturing information, could be achieved within the Rhinoceros 3D, Grasshopper, and Silkworm workspace.

Silkworm outputs the G-code needed for printing. For extrusion based printing processes, the main commands in the G-codes body are the following;

-G1; the command defining the line of text as a movement code

-XYZ co-ordinates: The position for the printe head to move to, defined by the Cartesian coordinate system in x,y,z units (mm). In this case set absolute positions, so units are absolute rather than in relation to the previous point

-F (Feedrate); the speed of the printers linear motions (mm/minute)

-E; (Extrusion); The amount of material extruded (mm). In this case set to relative so it defines the amount of material between the current, and previous point

Motion and extrusion command line example;
G1 X20 Y50 Z0.3 E0.5 F100 (The order that the XYZ, F, and E values are stated does not matter)

Grasshopper/Silkworm scripts were developed to define these positioning commands, F-speed, E-rate, as well as integrate the need start and end code commands. These are explained further, in the computational and software development stages of parts 2.1 and 3.1.

G-CODE TO PRINT

Below: Figure 28. Author, G-code to Print MB

G-code from Grasshopper/Silkworm

Pasted into Notepad++ and saved as a .gcode file

Then run through a converter to be readable to a Makerbot (.x3g file)

A small process was needed to get the G-code into a readable format for the Makerbot, as seen in Figure 28. The G-code output from Grasshopper/Silkwork was copied into Notepad++ where any adjustments to the text could be completed. This is then saved as a .gcode, and subsequently converted to a .x3g, the format that the Makerbot prints from, though a GPX G-code to x3g converter. This is then put onto a Makerbot specific SD card to be printed directly through the Makerbot.

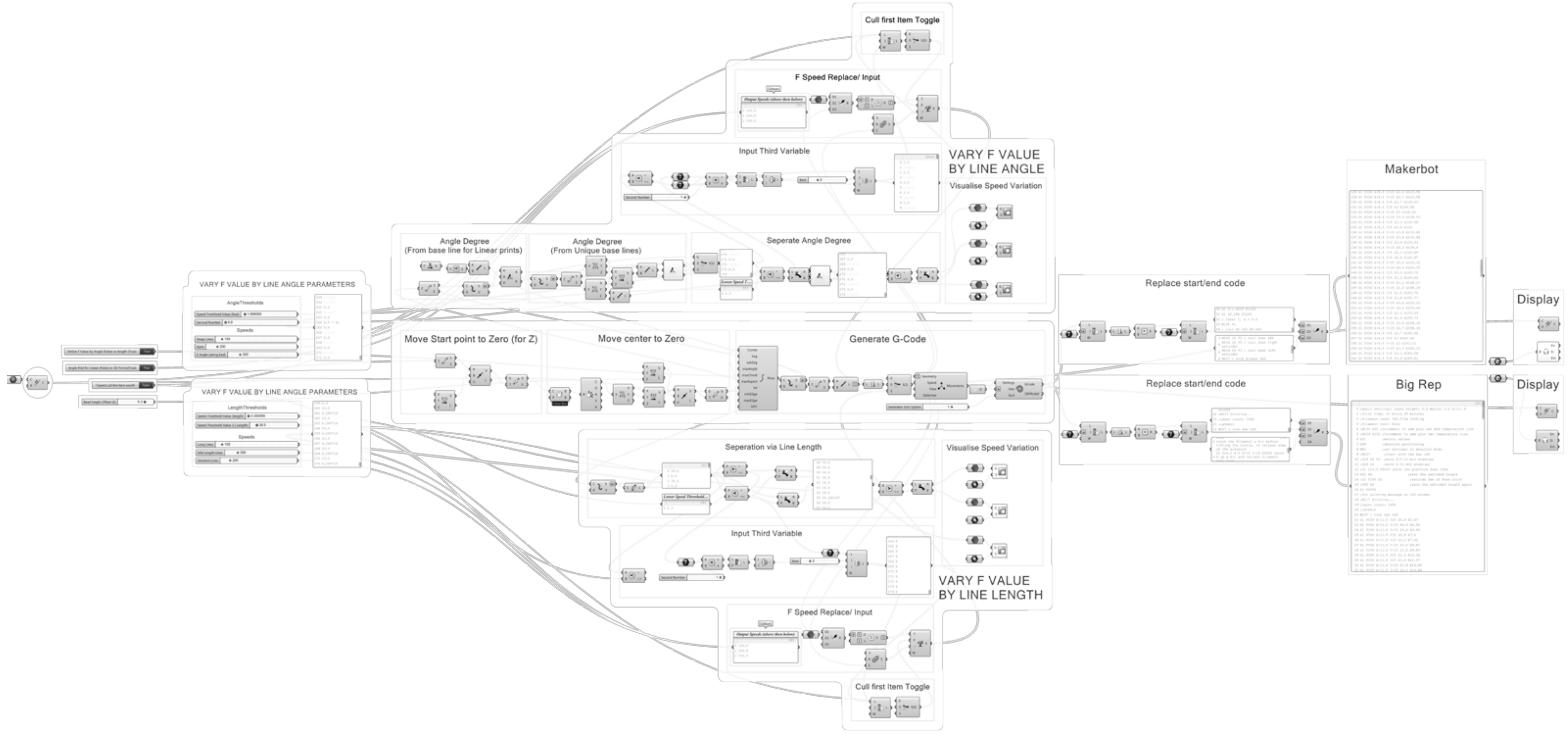


Figure 29. Author, Grasshopper Script Iteration 1

COMPUTATIONAL AND SOFTWARE DEVELOPMENT

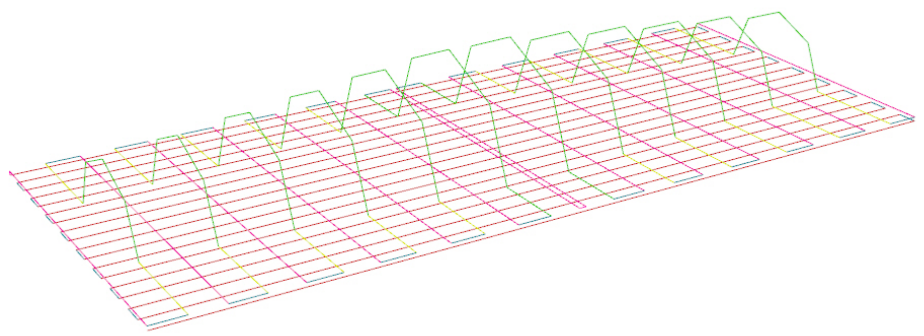


Figure 30. Author, Toolpath Colour Key

Figure 29 shows the first script developed for creating G-code. Through a self-taught process, this grew as knowledge of the programmes and printing process increased.

The settings and relationships between line length, line angle, extrusion rate, feed rate and temperature were unbeknownst at this stage. Thus, parameters and options were set within the script as to how the G-code was generated and how relationships were defined. Codes or keys were put in place of the F and E rates and 'find and replace' within Notepad++ was used to manually change these with various settings to test. These could be defined by factors such as line lengths, ie. line lengths within a certain range would be replaced with one key (colour or number) and line length within another range replaced with another and so on. This premise could be used for angles, either angle from the base plane, or from the last curve, or depending on whether the Z value increased or not.

Parameters and what was defining the key codes were adjusted depending on the requirements of the test print at hand.
Figure 30 shows an example of the preview of how lines were separated, in this example by length. Each colour would have a number key that would be replaced with the desired speeds and extrusion rates.

This script was developed with the intention to streamline once the appropriate settings and relationships had been defined.

SETTINGS TESTS - NOZZLE 1 (N1)

N1 - Longer than N0, in body and Nozzle Length. Increased tip angle and extrusion diameter.

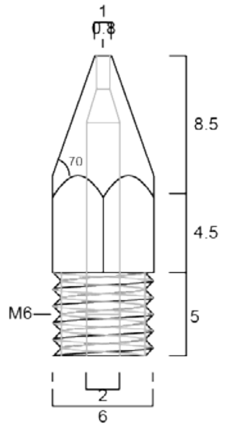
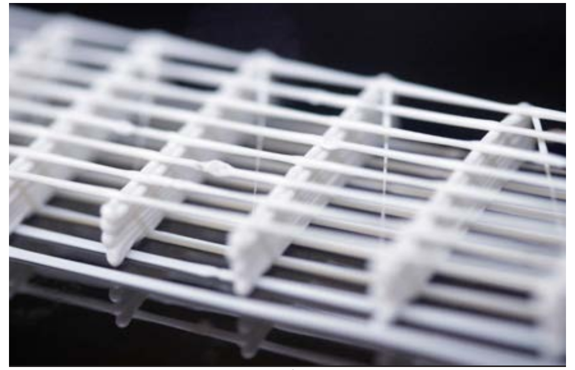


Figure 31. Author, N1 Dimensions

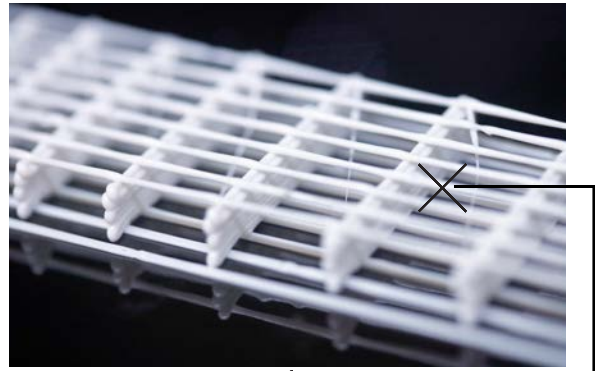
The following pages are the results of settings tests using Nozzle 1 (N1), as seen in Figure 31.

N1 TEMPERATURE TESTS (N1TT)

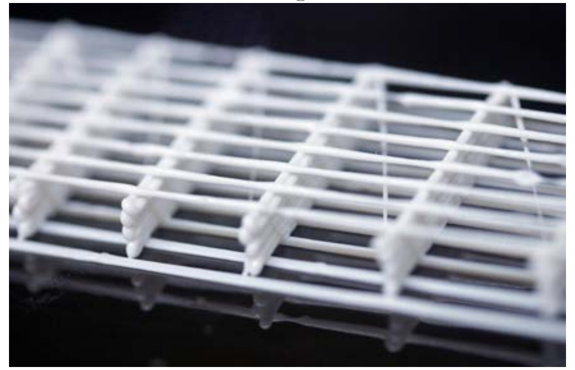
Temperature tests considering effect on adherence between layers, bridging, drooping of material and quality of material. Tests were undergone at temperatures between 230 - 260, at increments of 10 degrees. As seen in Figure 32.



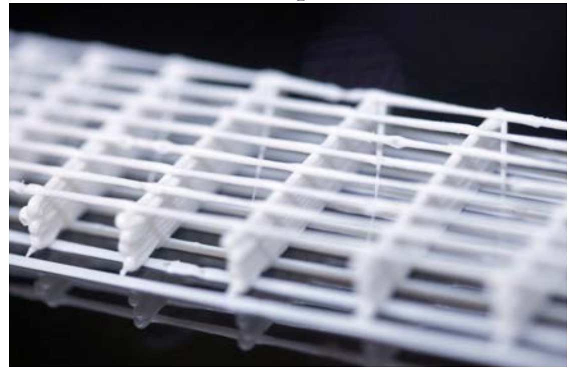
230 degrees



240 degrees



250 degrees



260 degrees

Figure 32. Author, N1TT

Findings

Over the temperature range, filament width stayed mostly consistent, and there was little effect on quality of bridging and adherence. At higher temperatures texture and bubbling of the material increases, and quality decreases. Around 240 degrees celsius was found to be a reliable temperature.

NOZZLE 1 BRIDGE TESTS (N1BT)

Bridging tests to find appropriate F Speed and E rate for unsupported print strands. Tested were F Speeds of 500, 1000, 1500, 2000, with two bridged strands per variable E-rate, to cover print direction influence - E-rate increasing in Increments of 2.5. Two prints per F rate, Print 1; E50 - E32.5, and Print 2; E30 - E12.5). Support structures were built at increasing distances from 4mm to 15mm at 1mm increments. Layer offset of 0.6mm.

Optimum relationships of the F Speed and E-rate decided with consideration to effects on adherence between layers, bridging and drooping of material, and quality of material.

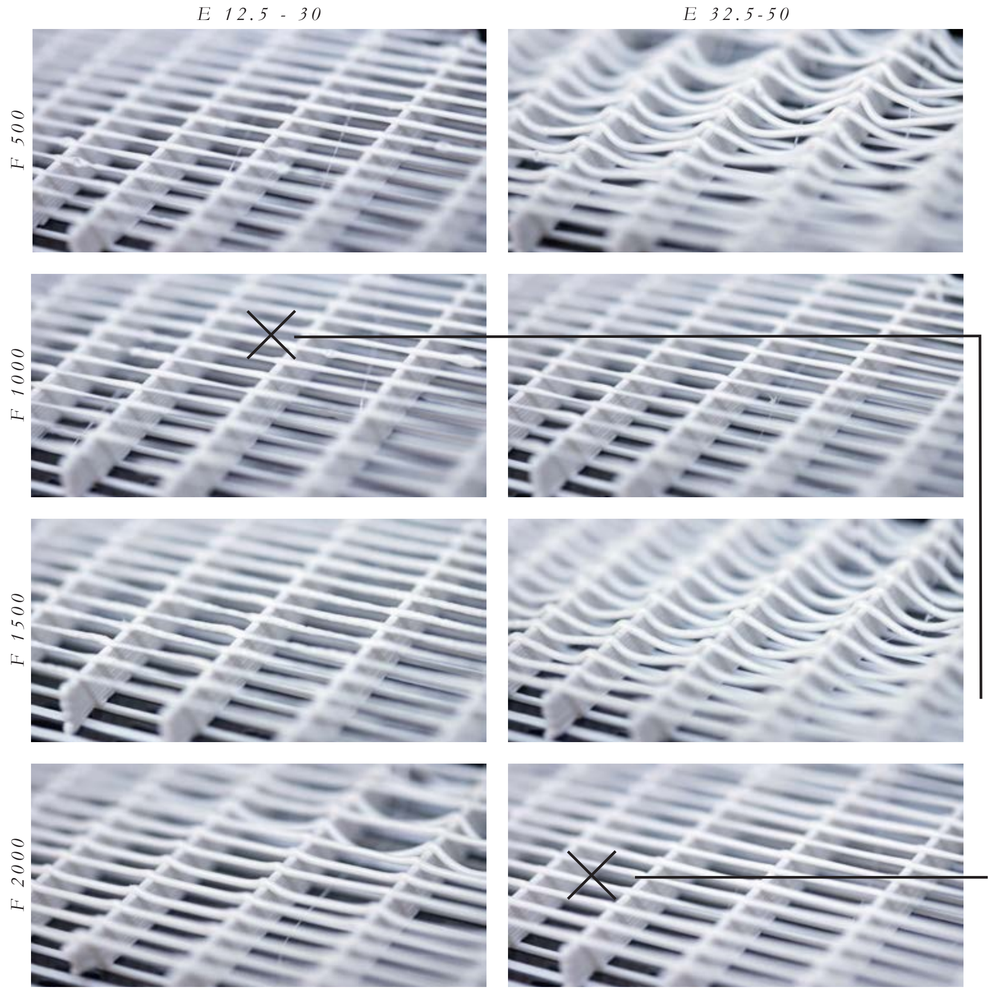


Figure 33. Author, N1BT

N1BT OPTIMUM SETTINGS

Two optimum relationships were apparent, one for producing a thicker bead and the other thinner;

Optimum Thinner E25-20 with F1000 -

Consistent diameters but thinner outcome, good material quality.

Optimum Thickest E 27.5 - 35 with F2000 -

Creates most consistent + and thickest self -supporting bead, good material quality.

NOZZLE 1 BRIDGE TESTS - LONGER BRIDGING DISTANCE (N1BTL)

Testing with optimum settings found of N1BT with speeds 1000, 2000, with two bridged strands per variable E-rate, to cover print direction influence. E-rate increasing in Increments of 2.5. Print 1; F1000, E15- E25, and Print 2; F2000 E27.5 - E35. Testing with increased distances between supports of 65mm, 75mm, and 85mm. Layer offset of 0.6mm. Optimum relationships of the F Speed and E-rate were decided with consideration to effects on adherence between layers, bridging and drooping of material, and quality of material.

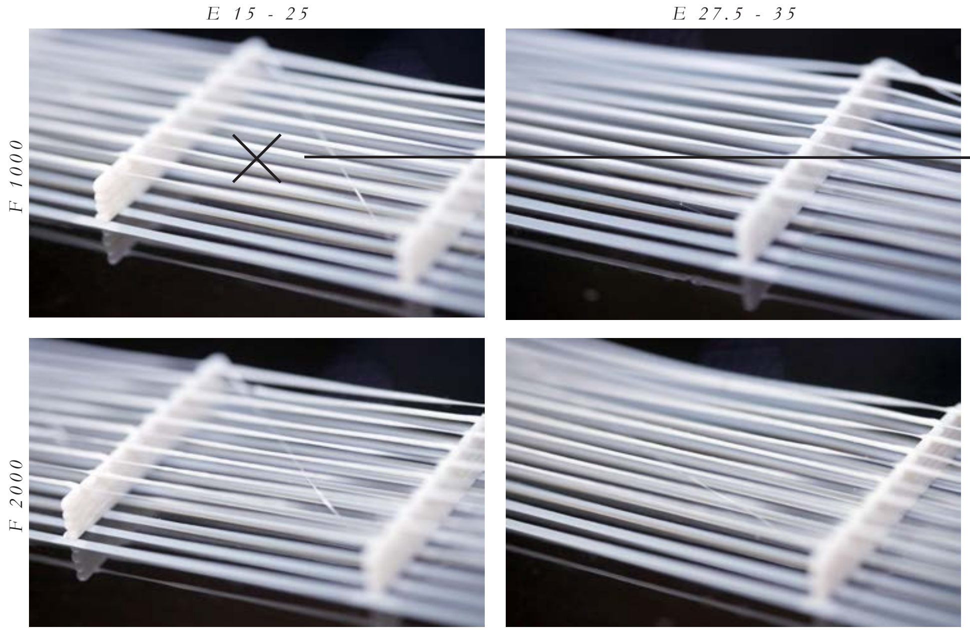


Figure 34. Author, N1BTL

N1BTL OPTIMUM SETTINGS

Most strands were generally successful and comfortably reached the maximum distance of 85mm.

It appears that the slower speed is slightly better with the increased distances (F1000), a slower E-rate (20-25) works best with this.

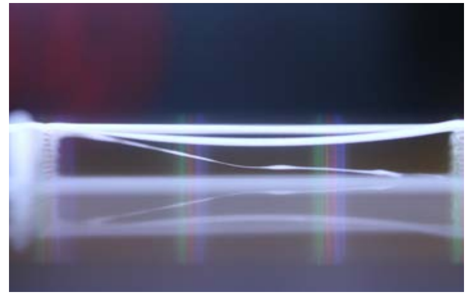


Figure 35. Author, Filament Droop

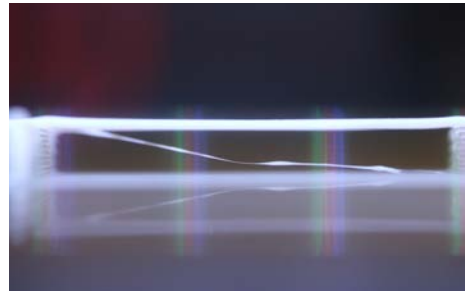


Figure 36. Author, Filament Contract

OTHER FINDINGS

Once the filament is extruded placed between supports, the filament droops quite low (seen in Figure 35), and subsequently retracts and even out to a supported straight line as it cools (Figure 36), possibly due to ABS's shrinkage properties as it cools.

SETTINGS TESTS - NOZZLE 2 (N2)

Nozzle 2 (N2) - Longer in body than N1, but extrusion tip diameter, length and angle the same.

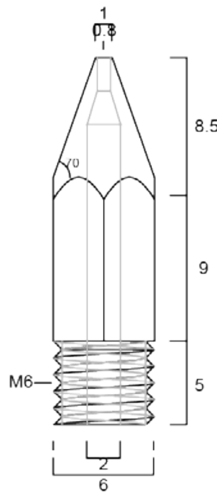


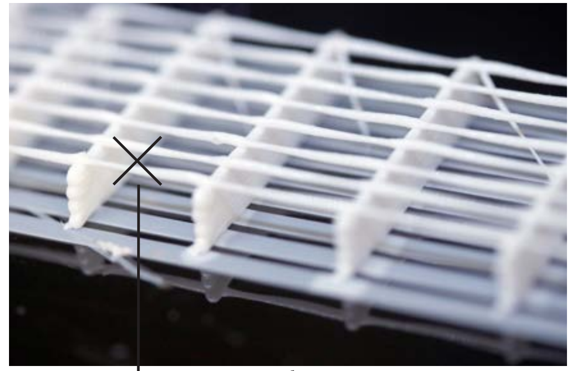
Figure 37. Author, N2 Dimensions

It became clear that the more the nozzle in use protrudes beyond the printer, the more freedom there became in Z height motions. For this reason, a new longer nozzle was developed and new settings discovered.

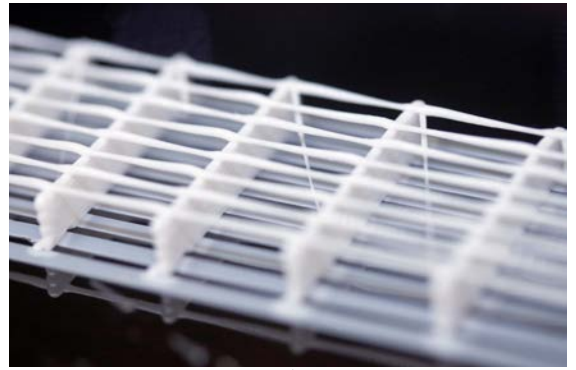
The following pages are the results of settings tests using Nozzle 2 (N2), as seen in Figure 37.

N2 TEMPERATURE TESTS (N2TT)

Temperature tests considering the effect on adherence between layers, bridging, drooping of material and quality of material. Tests were undergone at temperatures of 240 and 250 degrees.



240 degrees



250 degrees

Figure 38. Author, N2TT

Findings

Geometries were consistent between both tests and the materials are drooping / supporting themselves in the same manner. The material consistency at 250 degrees was slightly rougher than ideal, so keeping with the current temperature of 240 degrees celsius was found to be most appropriate.

NOZZLE 2 BRIDGE TESTS (N2BT)

Bridging tests to find appropriate F Speed and E-rate for unsupported print strands. Tested were F Speeds of 500, 1000, 1500, 2000, with two bridged strands per variable E-rate, to cover print direction influence - E-rate increasing in Increments of 2.5. Two prints per F-rate , Print 1; E50 - E32.5, and Print 2; E30 - E12.5). Support structures were built at increasing distances from 4mm to 15mm at 1mm increments. Layer offset of 0.6mm.

Optimum relationships of the F Speed and E-rate decided with consideration to effects on adherence between layers, bridging and drooping of material and quality of material.

E 12.5 - 30 | E 32.5-50

F 1000 | F 1500 | F 2000

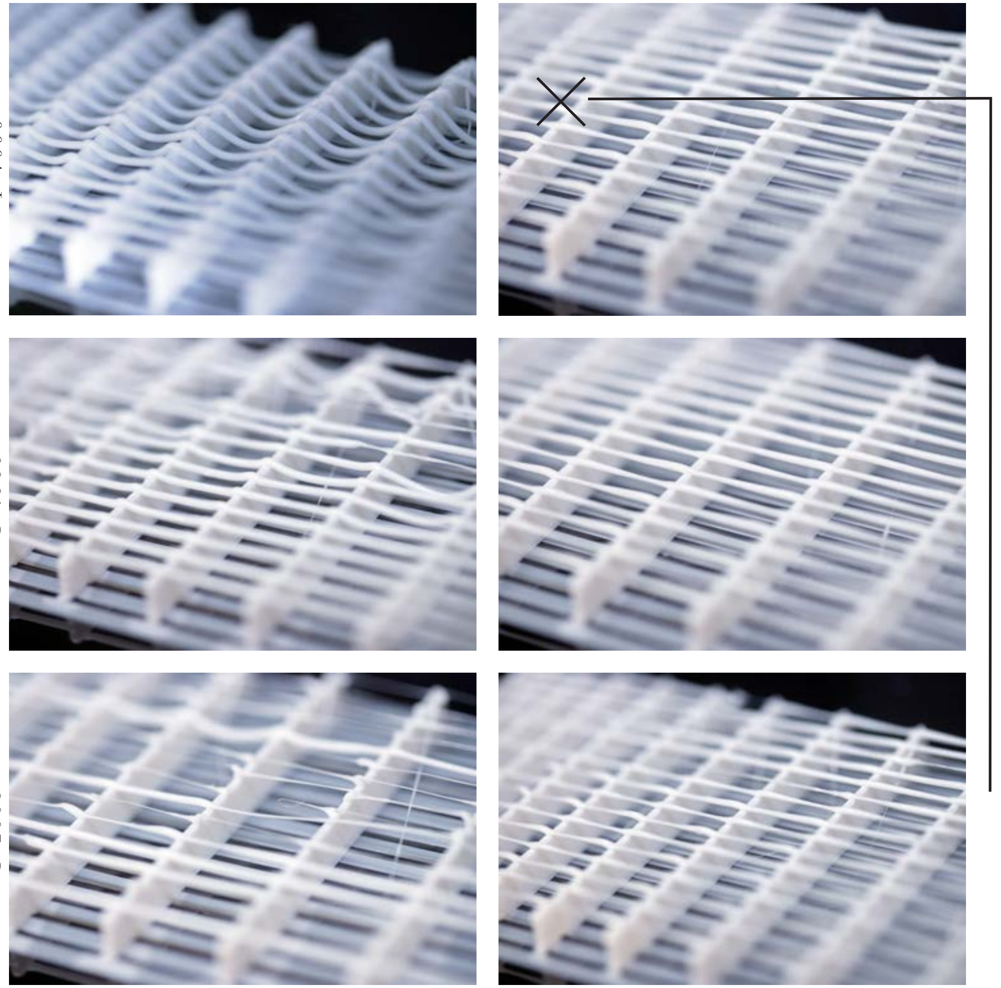


Figure 39. Author, N2BT

N2BT OPTIMUM SETTINGS

F 1000 E25-35 -
Creates most consistent self-supporting bead, good material quality.

Similar to Optimum of N1BT and N1BTL But with a slight increase in E-rate needed.

NOZZLE 2 BRIDGE TESTS - LONGER BRIDGING DISTANCE (N2BTL)

Testing with optimum settings found of N1BT with speeds 1000, 1500, with two bridged strands per variable E-rate, to cover print direction influence. E rate increasing in Increments of 2.5.Print 1; F1000, E15-E25, and Print 2; F2000 E27.5 - E35.Testing with increased distances between supports of 65mm, 75mm, and 85mm. Layer offset of 0.6mm.

Optimum relationships of the F Speed and E-rate were decided with consideration to effects on adherence between layers, bridging and drooping of material and quality of material.

E 25 - 35

F 1000 | F 1500

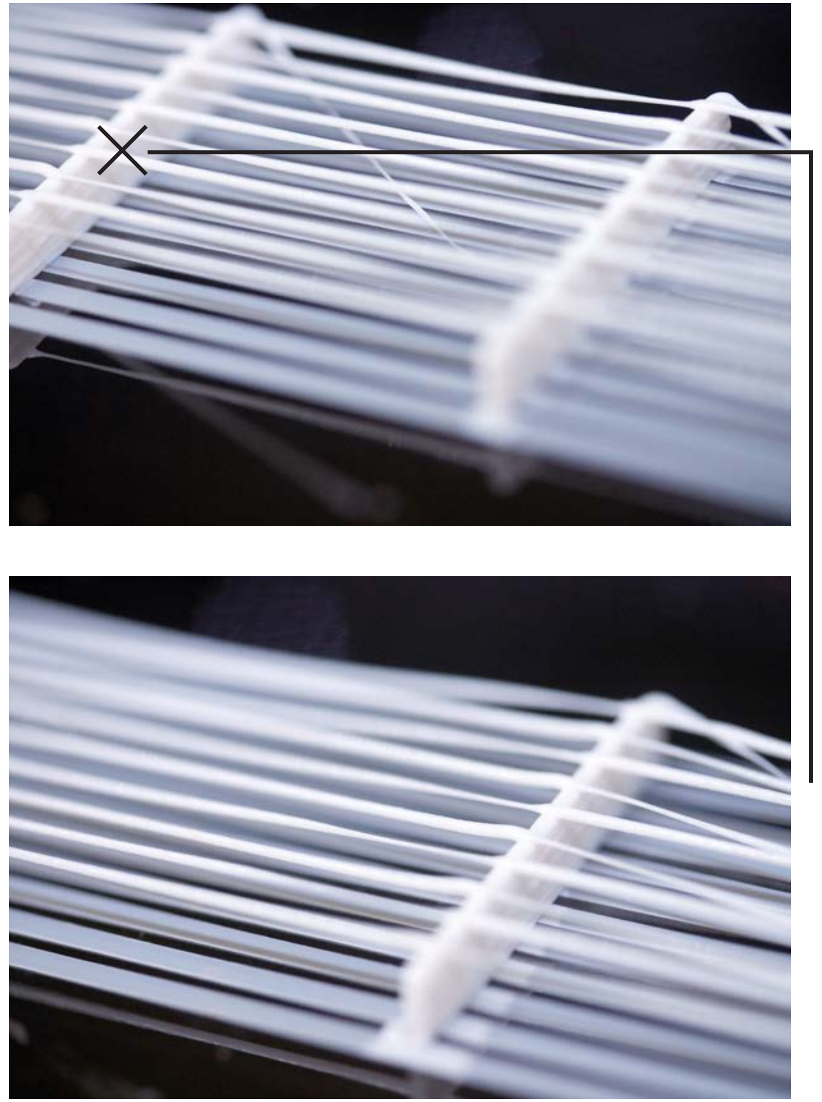


Figure 40. Author, N2BTL

N2BTL OPTIMUM SETTINGS

F1000 E27.5-32.5 or same as N2BT. At which the maximum length of 85mm was comfortably reached, with decent material quality and minimal droop.

On longer bridging distances the slightly higher speed (1500) starts to see a less consistent extrusion, thicker where it leaves support and thinner by the end of the unsupported length. Therefore, F1000 is more appropriate.

NOZZLE 2 ARC TESTS (N2AT)

Arc tests to discover appropriate settings for printing spatially. Arcs were low resolution (5 line segments per arc) to help keep settings clear and simple to interpret. Testing speeds F75, F100, F150 of 6 different arc sizes, (12 Arcs total with radii of 10,11,12,13,14, and 15mm). Two arcs were printed of each size is to compensate for directional pull. 3 E rates tested per F speed; E2, 2.5, and 3.

Print quality (smoothness/consistency), directional pull and height and shape retainment were all considered when deciding the most successful print settings.

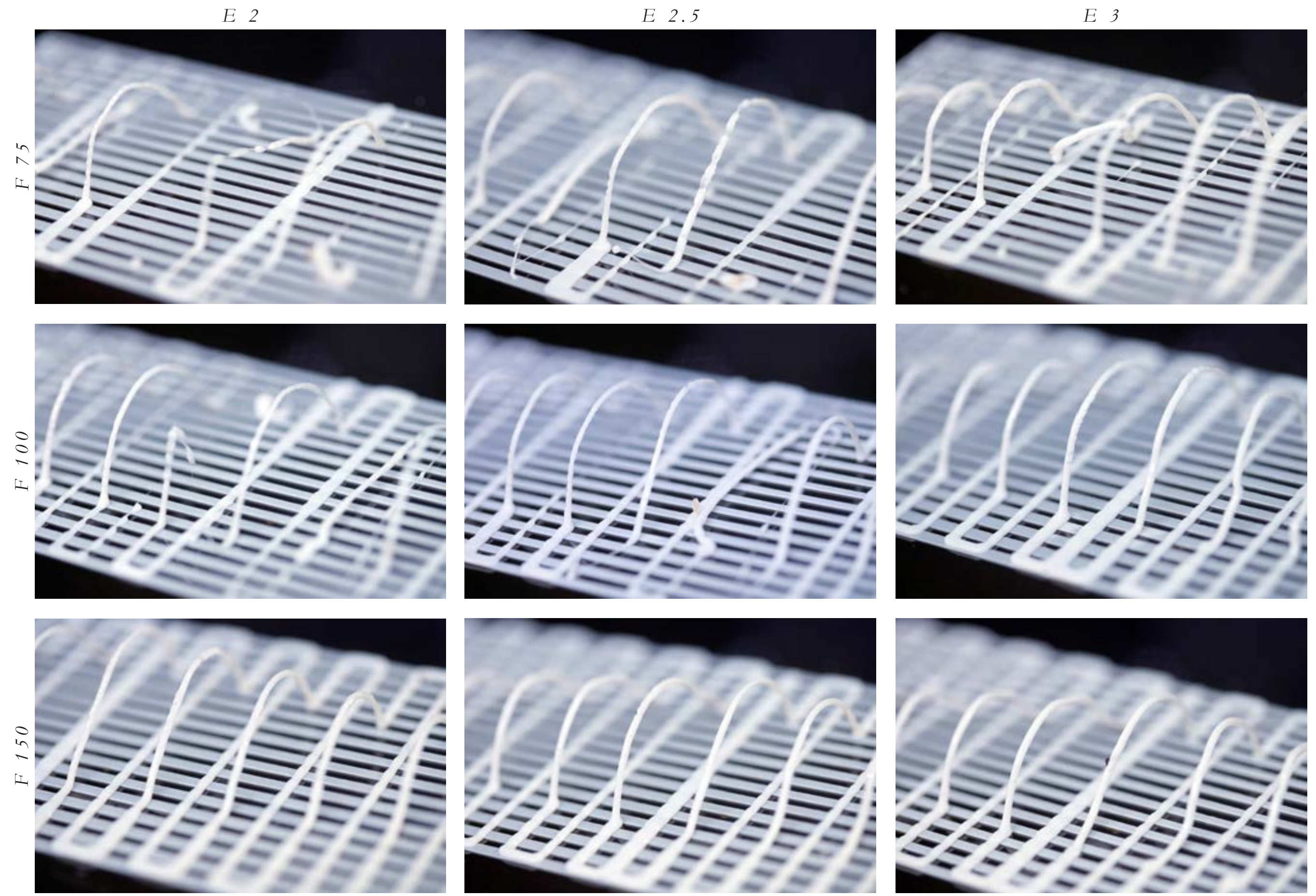


Figure 41. Author, N2AT

FINDING N2AT OPTIMUM SETTINGS

Tables used to find Appropraite E-rate dependant on line-lengths

LENGTH 7.5-8.5	E2	E2.5	E3	LENGTH ~9-10	E2	E2.5	E3	LENGTH ~ 10.5-11.5	E2	E2.5	E3
F75	D1			F75		D2		F75			D2
F100	D2 U1			F100	D1	U1		F100		D1	U1
F125				F125				F125			
F150				F150				F150			

L	E	
11	3	0.3
9.5	2.5	0.27
8	2	0.25

		E VAUE UP	E VALUE DOWN
Length	*.25	*0.3	*.8
7.6	1.9	2.28	1.824
8.3	2.075	2.49	1.992
9.14	2.285	2.742	2.1936
9.9	2.475	2.97	2.376
10.6	2.65	3.18	2.544
11.43	2.8575	3.429	2.7432

Figure 42. Author, N2AT Settings Tables

N2AT OPTIMUM SETTINGS

Different E rates and F speed relationships were best for different sized arcs, So in identifying the best-printed arcs of each radius variable and finding the relationship between the setting of this and the correlated lines length(s), the optimum settings could be calculated. The workings of this shown in Figure 42.

The speed of F100 was found to be the optimum print movement speed for printing these arcs and the E-rate was found to be best at between 0.25 - 0.3 times the line length.

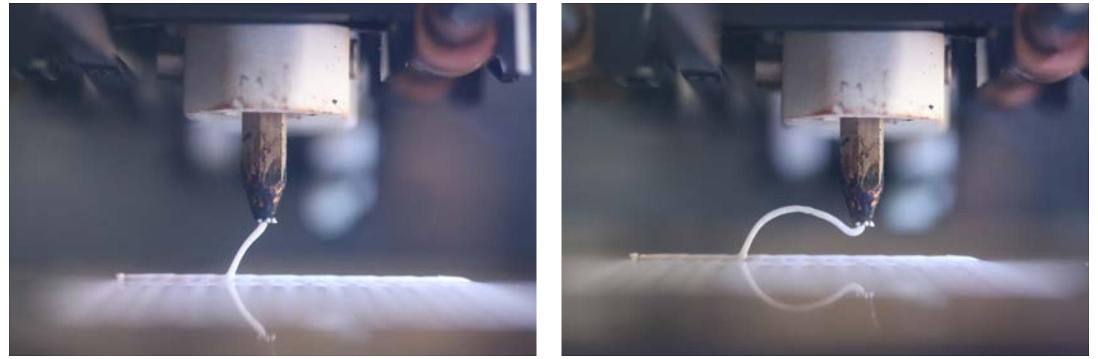


Figure 43. Author, N2AT Up vs Down

It was also discovered through the N2AT that the E-rate on the paths moving down (negative Z movements) needed to be slightly decreased compared to upward motions.
This was due to gravities pull on the filament, meaning that excess filament was printed during downward motions. This is compared to upwards motions during which the slight tension between the nozzle and printed geometry counteracts gravity (as seen in Figure 43).
A comfortable adjustment for negative motions was to times the calculated extrusion rate by 0.9.

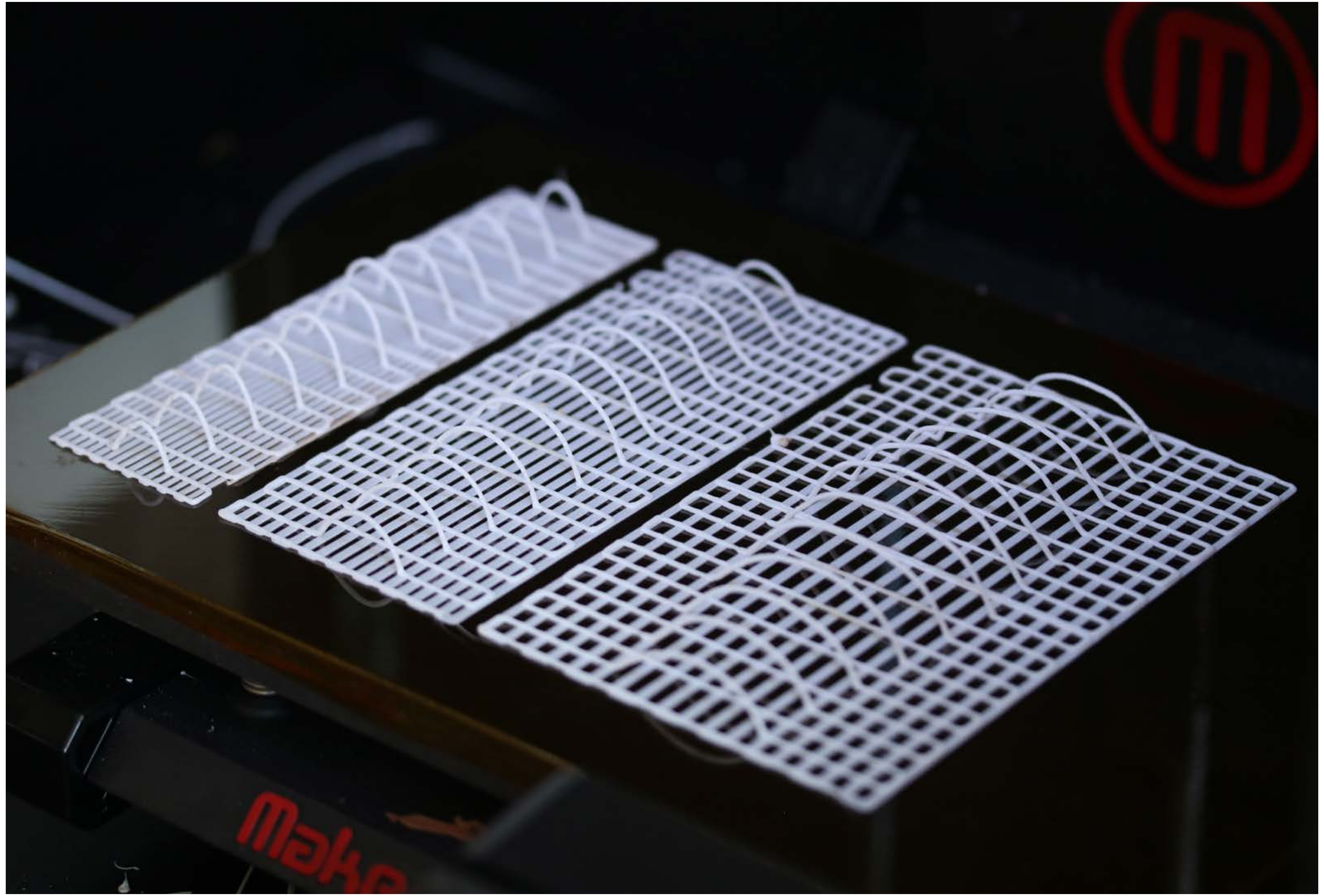


Figure 44. Author, N2AT Optimum Settings Check

SETTINGS TESTS OVERVIEW

Freeform Printing Settings

The arc tests proved it possible to print self-supporting strands spatially with the Makerbot Replicator 2X and ABS material. The optimum settings defined were found to create physical structures in very close reflection of that delineated digitally. The final settings produce prints with minimal deviation from the expected print height in the z direction, no more than 1mm, but with a small amount of deviation in the y direction, dependent on the direction that the arc was printed in. The print settings will be tweaked ongoingly to account for these slight deviations from the print path and minimise any undesired effects. Overall the settings were found to create a solid base for printing freeform structures close to what has been digitally defined.

To check the settings decided upon through the N2ATs, more prints using these relationships were produced, as seen in Figure 44. The middle print in this image is the same toolpath as used in N2ATs, but implementing the optimum relationships as found for each line. The prints either side are the same toolpath but increased or decreased in width, to test the settings with different angles and proportions. These proved to be as successful as the central arc test.

Planar Printing Settings

The print settings relationships when printing in planar formats are much less fastidious than during spatial printing. Adjustments can be made to cater for different requirements, like a thinner or thicker bead within certain parameters. These settings will be used for areas such as initial planar deposition of material onto the print bed, or any sections that are supported or planar in motion, ie. any printing in which the Z axis does not deviate (only XY motions).

With the nozzle diameter of 0.8, an offset of 0.6 was found appropriate for layered sections. A reduced offset is needed for the first layer (0.3-0.5mm) to ensure good adhesion to the bed base.

N2 SETTINGS

These new settings became implemented into an updated grasshopper script. Any line with a spatial motion (Z axis movement) will be attributed the freeform print settings (found from the N2AT). And all 2D motions (no z axis motions) attributed the planar print settings (found from N2BT and N2BTL). These will be printed at 240 degrees, as found suitable from the N2TT.

These will be referred to as the N2 Settings.

UPDATED GRASSHOPPER SCRIPT

The N2 setting were used to developed an updated grasshopper script. This script was developed and added to throughout the projects.

Below: Figure 45. Author, Grasshopper Script Iteration 1

The script takes one input curve (the intended toolpath), and splits it into small lines of motion. Each of these lines are then found to be either planar or spatial, and up or downwards in motion. The appropriate settings are applied to each section, depending on its length and direction. Other aspects of the script are for things such as relocating the toolpath to the centre of the bed and outputting G-code.

The N2 Settings were input as adjustable parameters so that they could be easily adapted throughout the research.

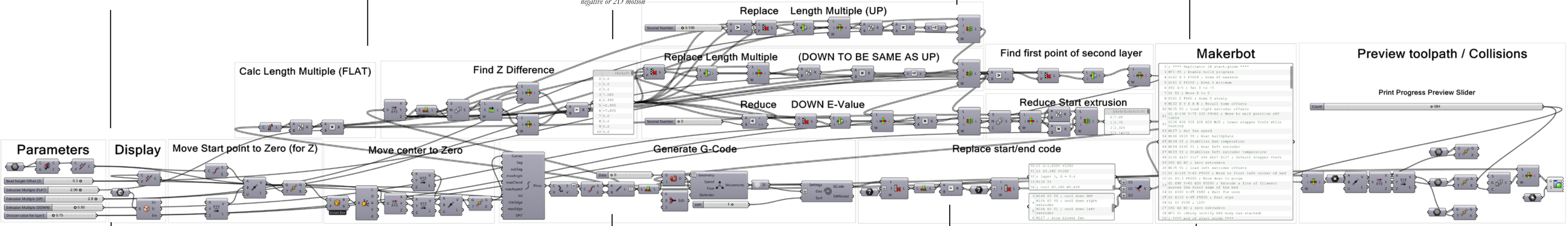
Toolpath / geometry input. Option to flip curve to define where start and end points are

Calculate Extrusion rate for flat 2D lines

Find difference of angle between one point and the previous point to determining if moving in positive, negative or 2D motion

Generate Extrusion rate for motions moving at a positive angle (up)

Final G-code output



Adjustable parameters to change aspects such as extrusion and movement speeds, bed offset etc

Relocate the path to the centre of the print bed

Silkwom script that breaks curves into printing segments and generates each movement point location

Generate Extrusion rate for motions moving at a negative angle (down)

Integrate start and end print code with the nessacary text for the Makerbot replcator 2X

Preview section, explained in full on the next page

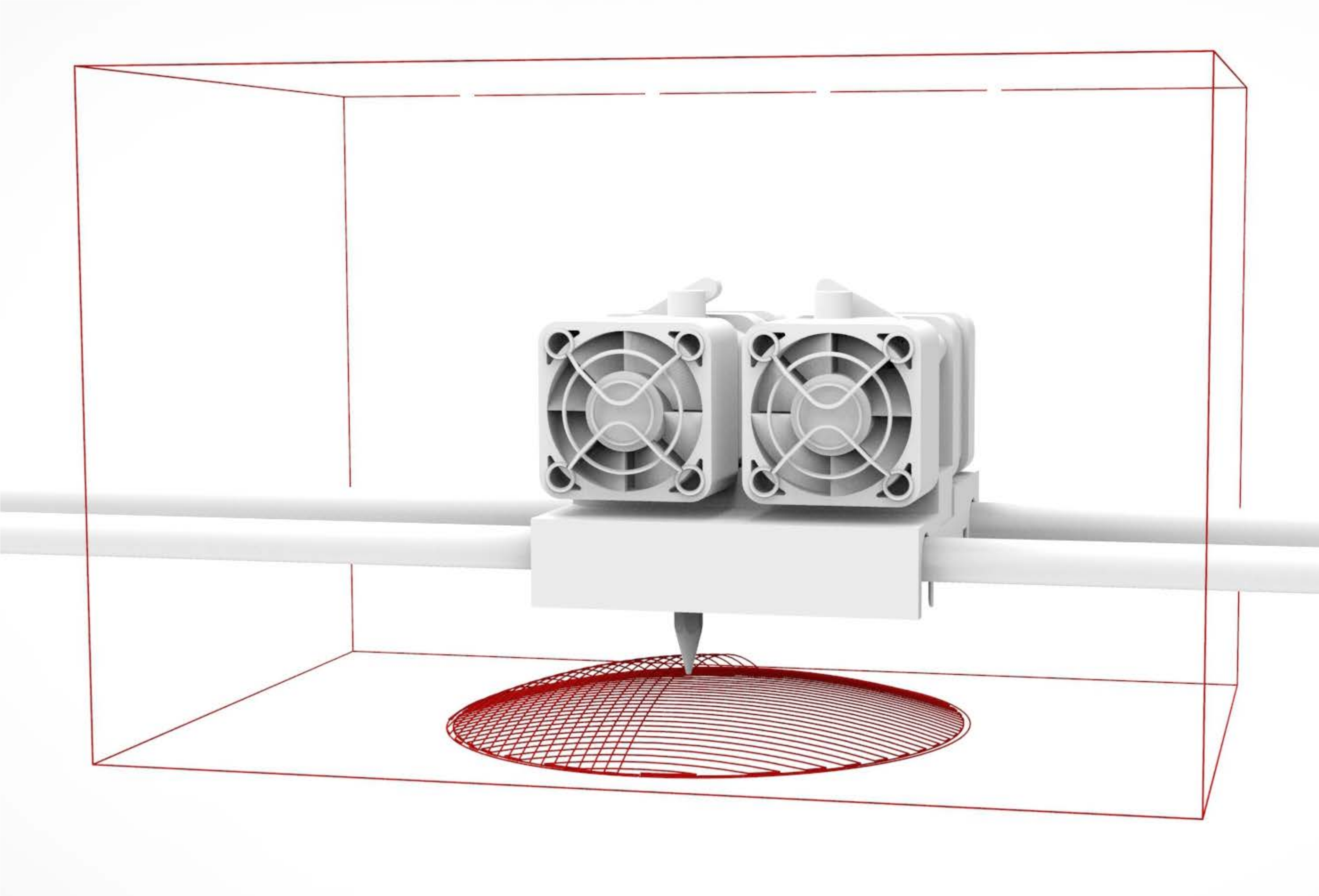


Figure 46. Author, Toolpath Preview 1

TOOLPATH PREVIEW

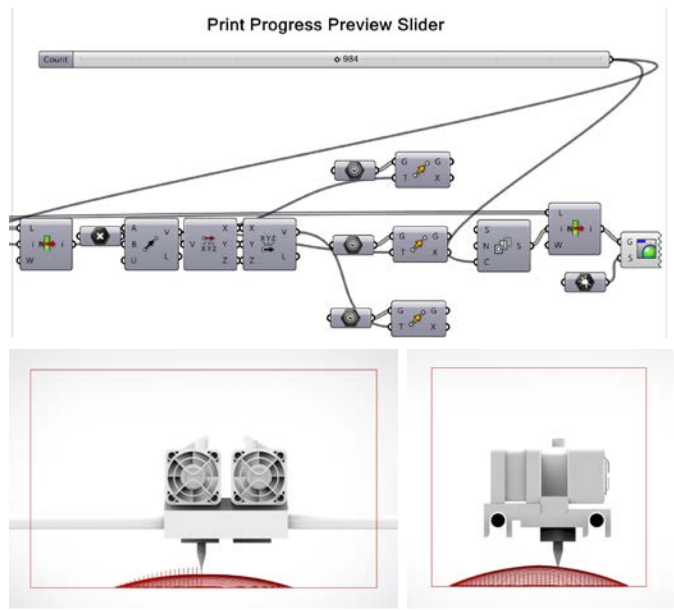


Figure 47. Author, Toolpath Preview 2

A simple but import addition to the script was the integration of a toolpath preview. The existing extruder geometries and nozzle in use were modelled. Using a slider to preview the toolpath up to a defined point, the tip of the nozzle and surrounding model of the extruder head move along the curve, expressing the path of the printer.

The main use of this was to determine points of collision between the printer and existing printed material. This means any required adjustments can be made before going through the final exporting and printing stages and saving valuable time. This was also used to check the toolpath was going to be printed in the intended direction, from the intended start to finish.

Figure 48. Author, Abstract Design Experiments

2.2 - ABSTRACT DESIGN EXPERIMENTS

The tests in the abstract design experiments sought to find and explore opportunities of spatial printing methods through the proposed form responsive method. Three series were developed with unique focuses testing opportunities of Designed Deposition. These were;

Series 1:
Minimal Base Adherence

Series 2:
Dynamic Layering

Series 3:
Structures, Patterns and Tectonics

SERIES 1: MINIMAL BASE ADHERENCE (MBA)

Minimal base adherence (MBA) is a series of abstract geometries investigating opportunities for the initial structural print deposition to create fully three-dimensionally considered structures. It tests techniques to avoid reliance on the base plane or on large quantities of support structured to build complex forms.

It is realised that most structures require a certain degree of bed adherence to build upon, but it is here tested how much the requisite for rafts or base build structures can be dismissed.

This series focused on geometries with non-planar bases, so the structure of the forms was filled with simple linear filament strands. Base curves were defined manually in Rhinoceros 3D, and linear structures were created in Grasshopper based off these, as demonstrated in Figure 49.

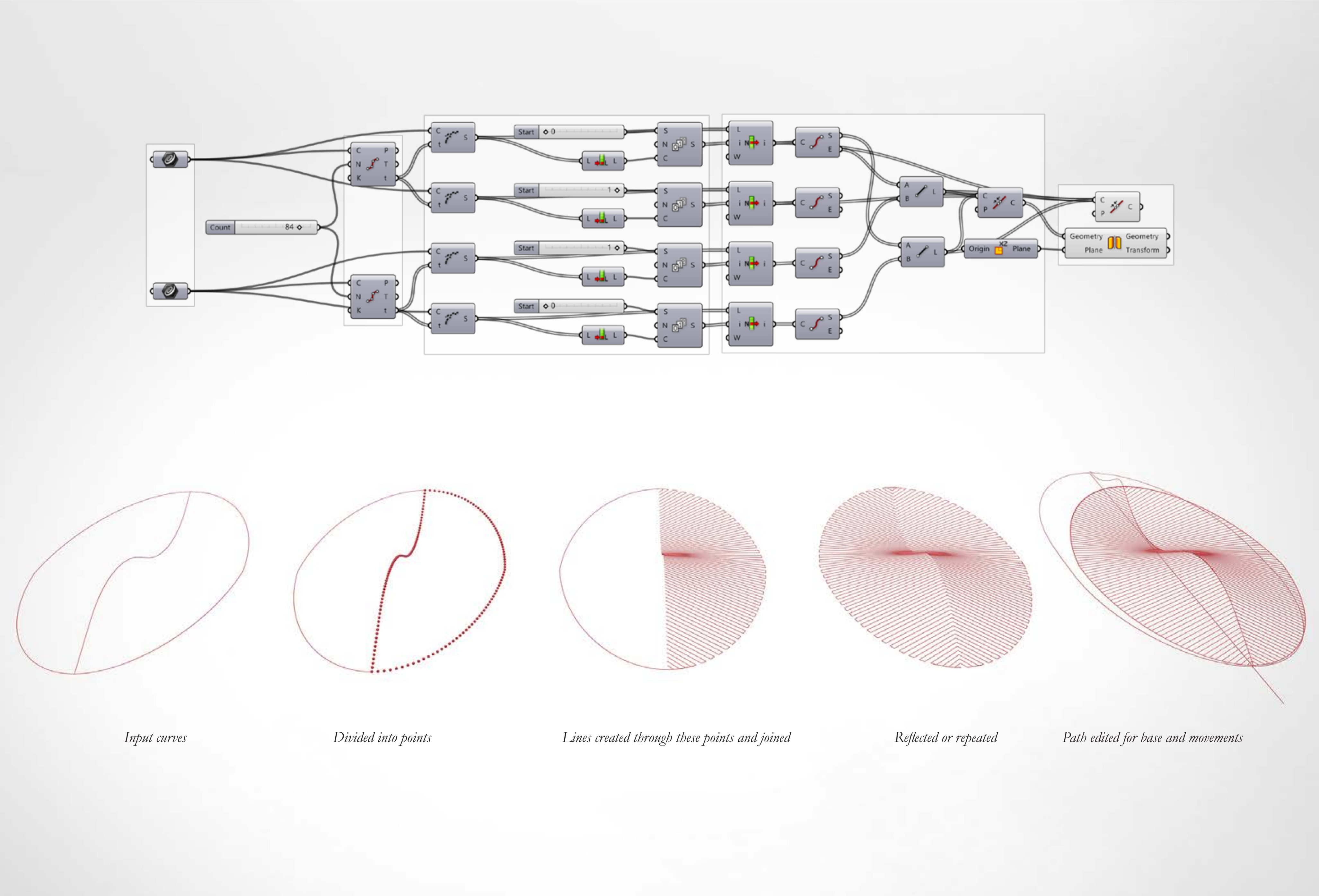
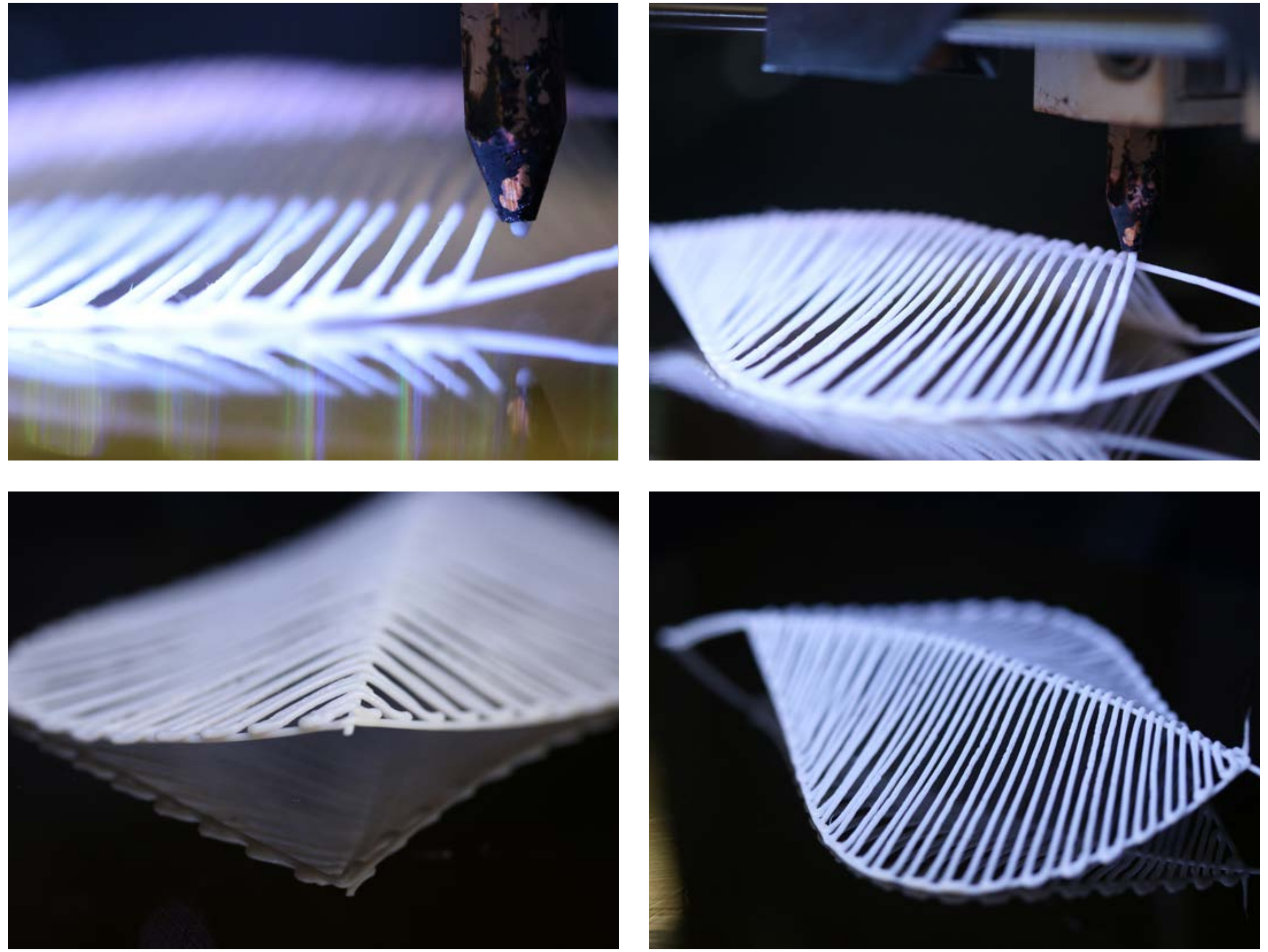


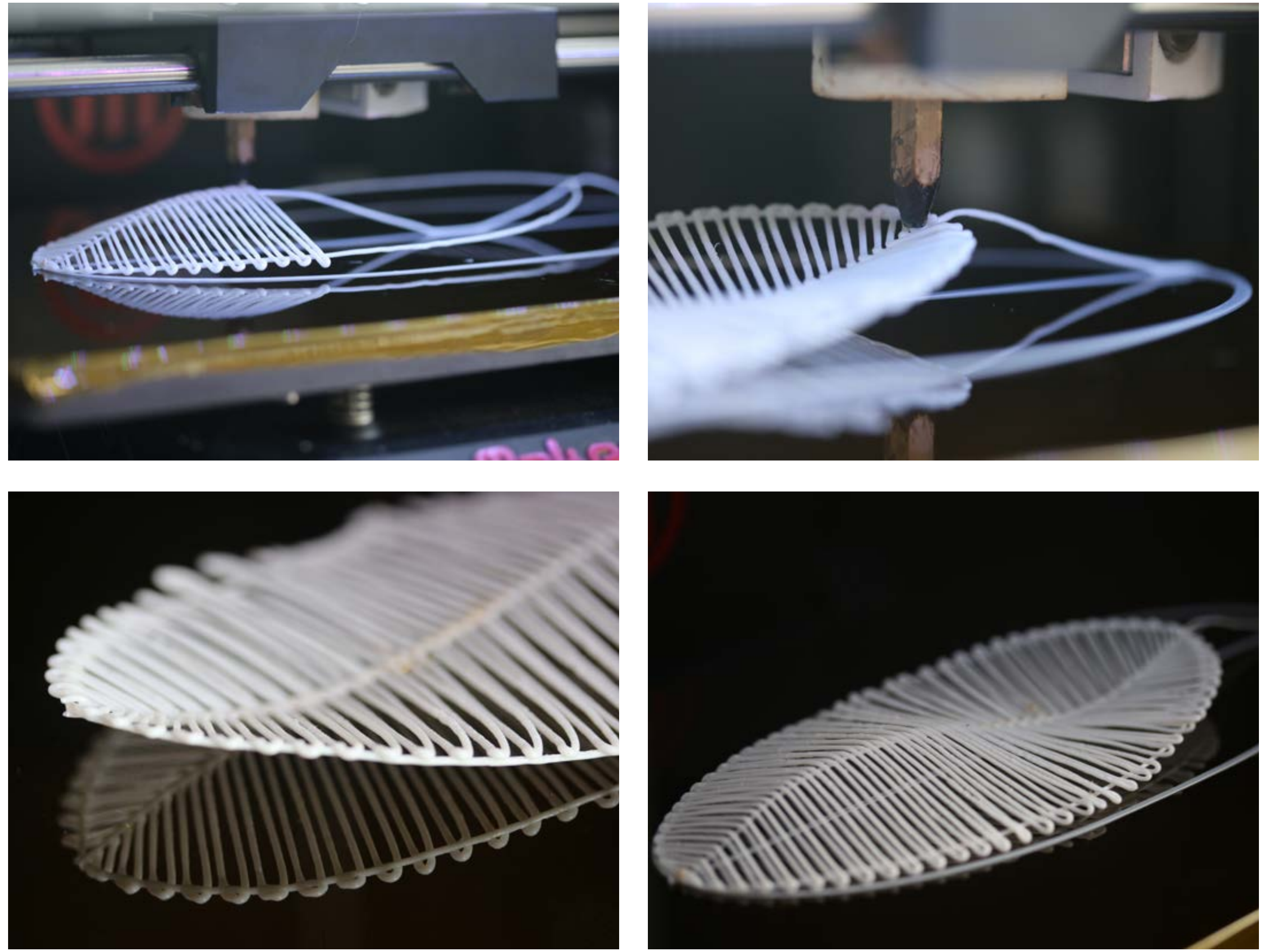
Figure 49. Author, MBA Modelling

Figure 50. Author, MBA Experiment 1



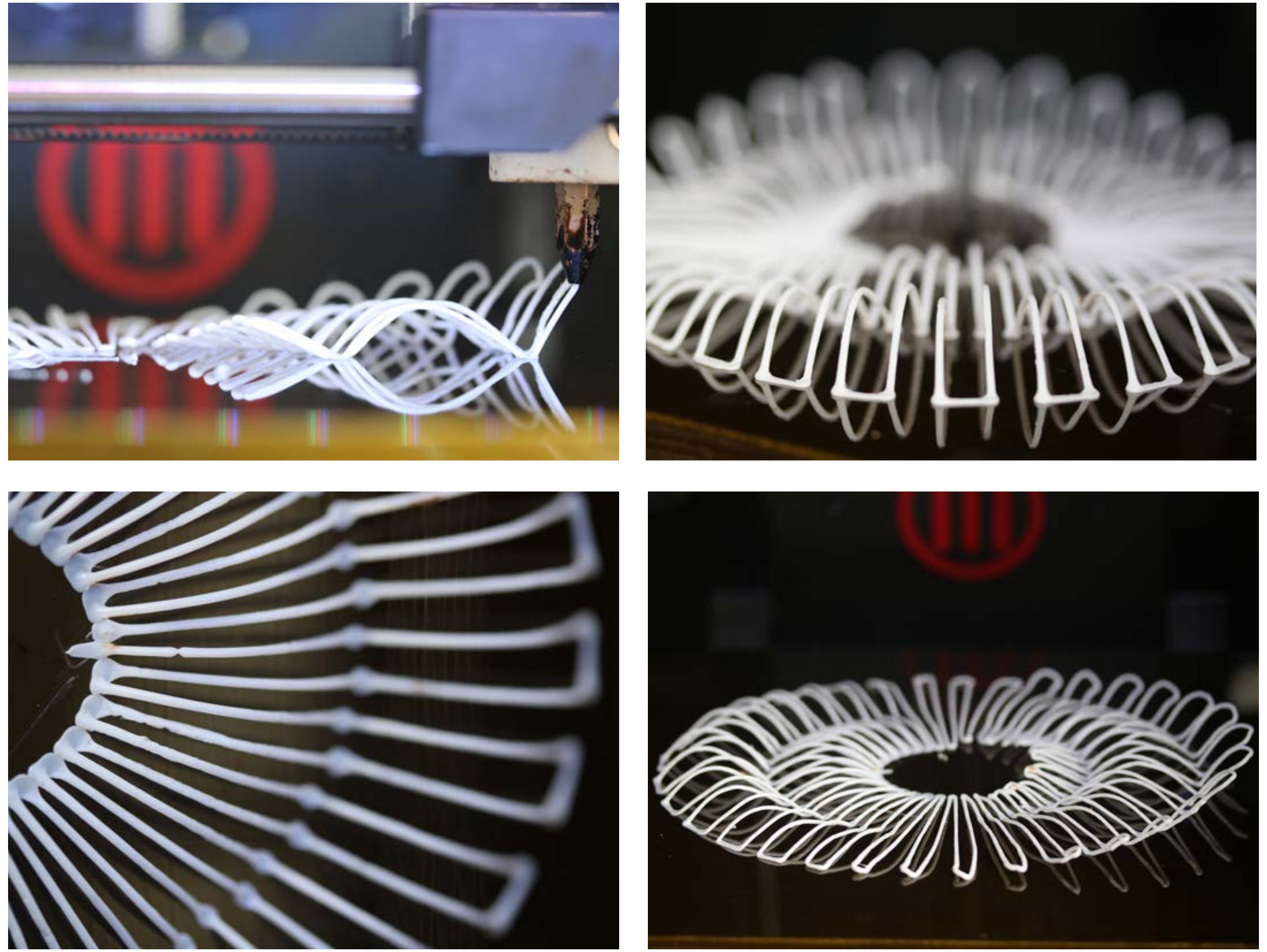
Print Time: 00.41.21
Material Used: 672mm White ABS
Nozzle : N2
Settings: N2 settings

Figure 51. Author, MBA Experiment 2



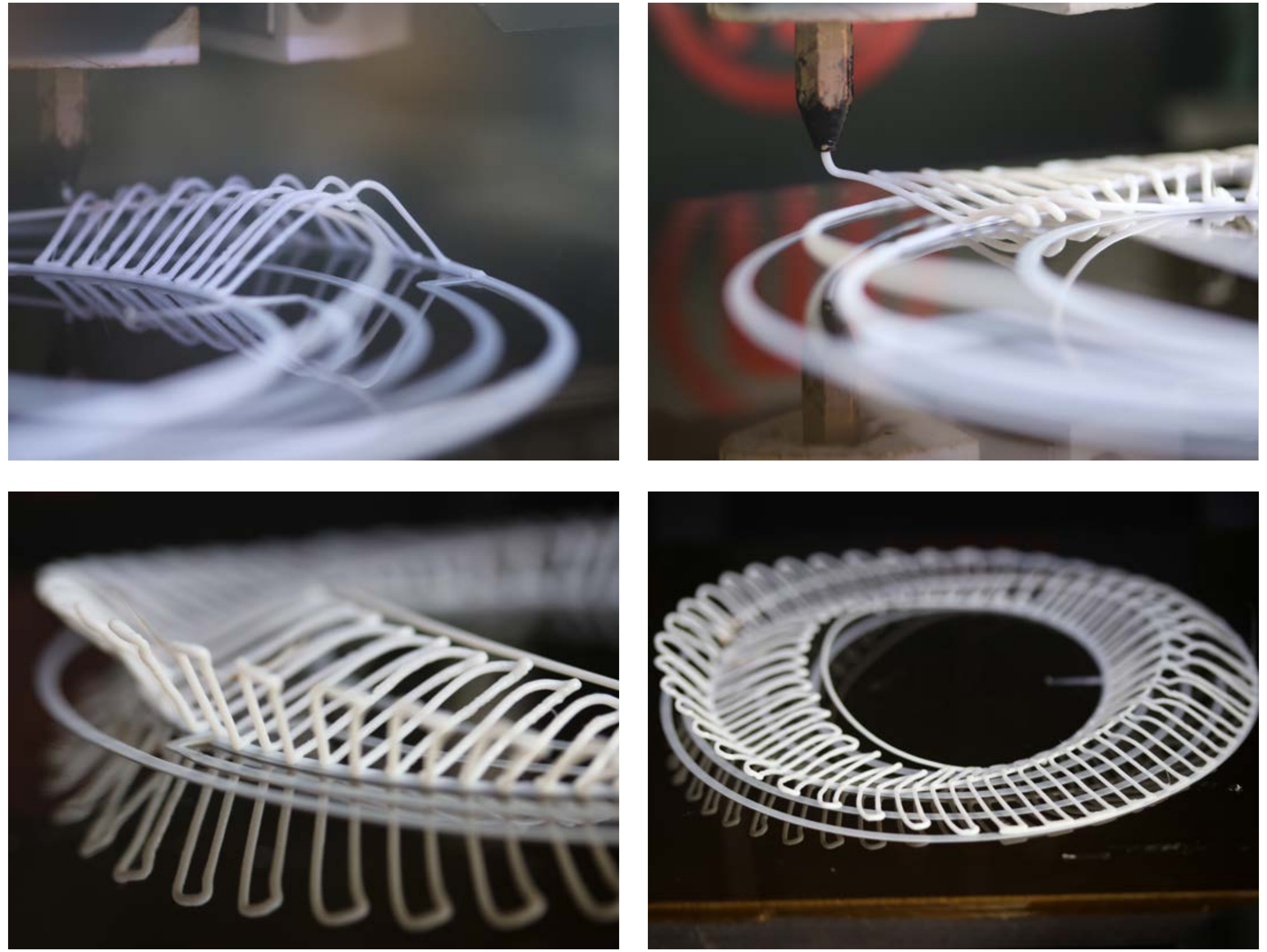
Print Time: 00.54:42
Material Used: 142mm White ABS
Nozzle : N2
Settings: N2 settings

Figure 52. Author, MBA Experiment 3



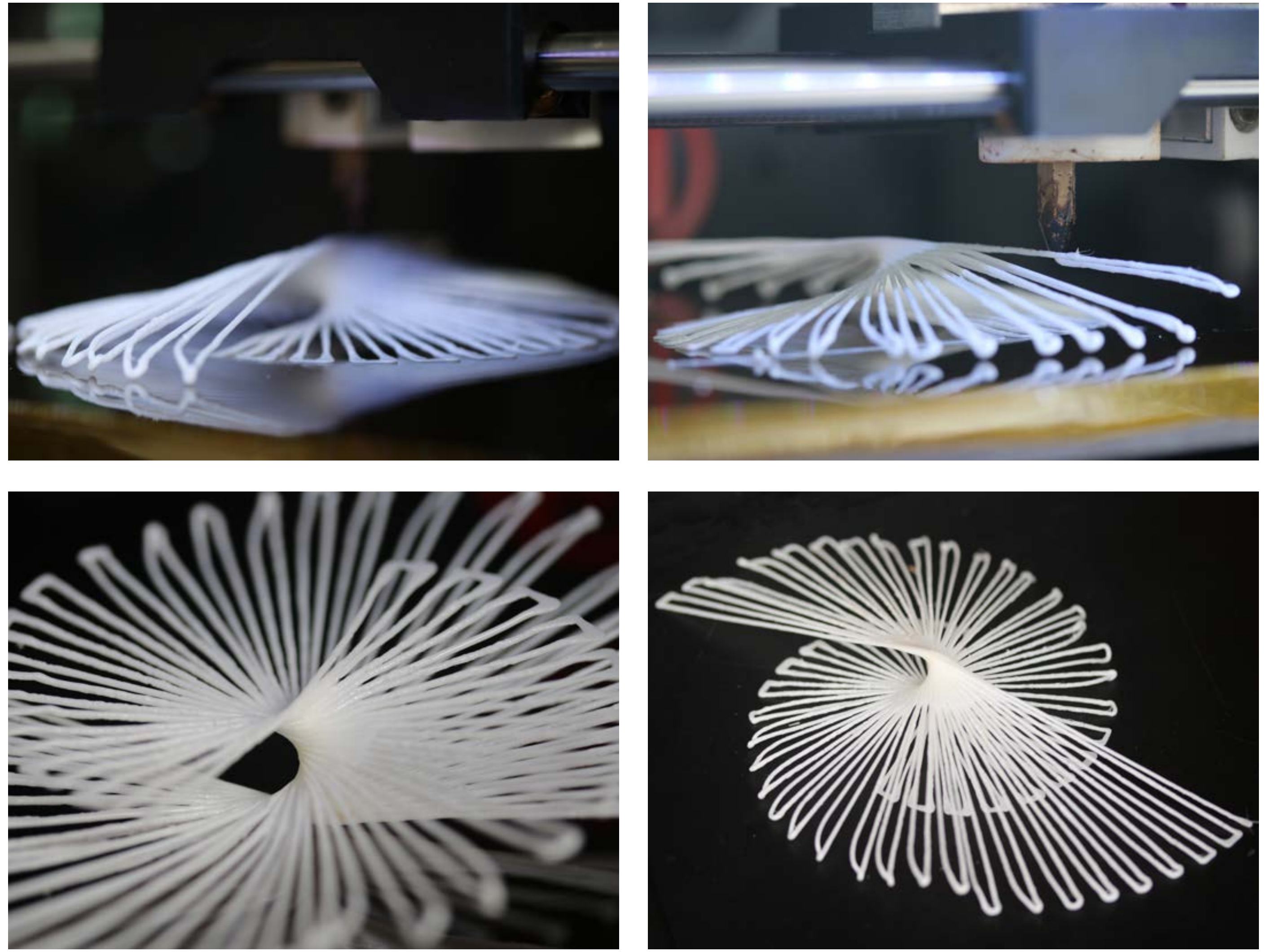
Print Time: 00.46:06
Material Used: 1163mm White ABS
Nozzle : N2
Settings: N2 settings

Figure 53. Author, MBA Experiment 4



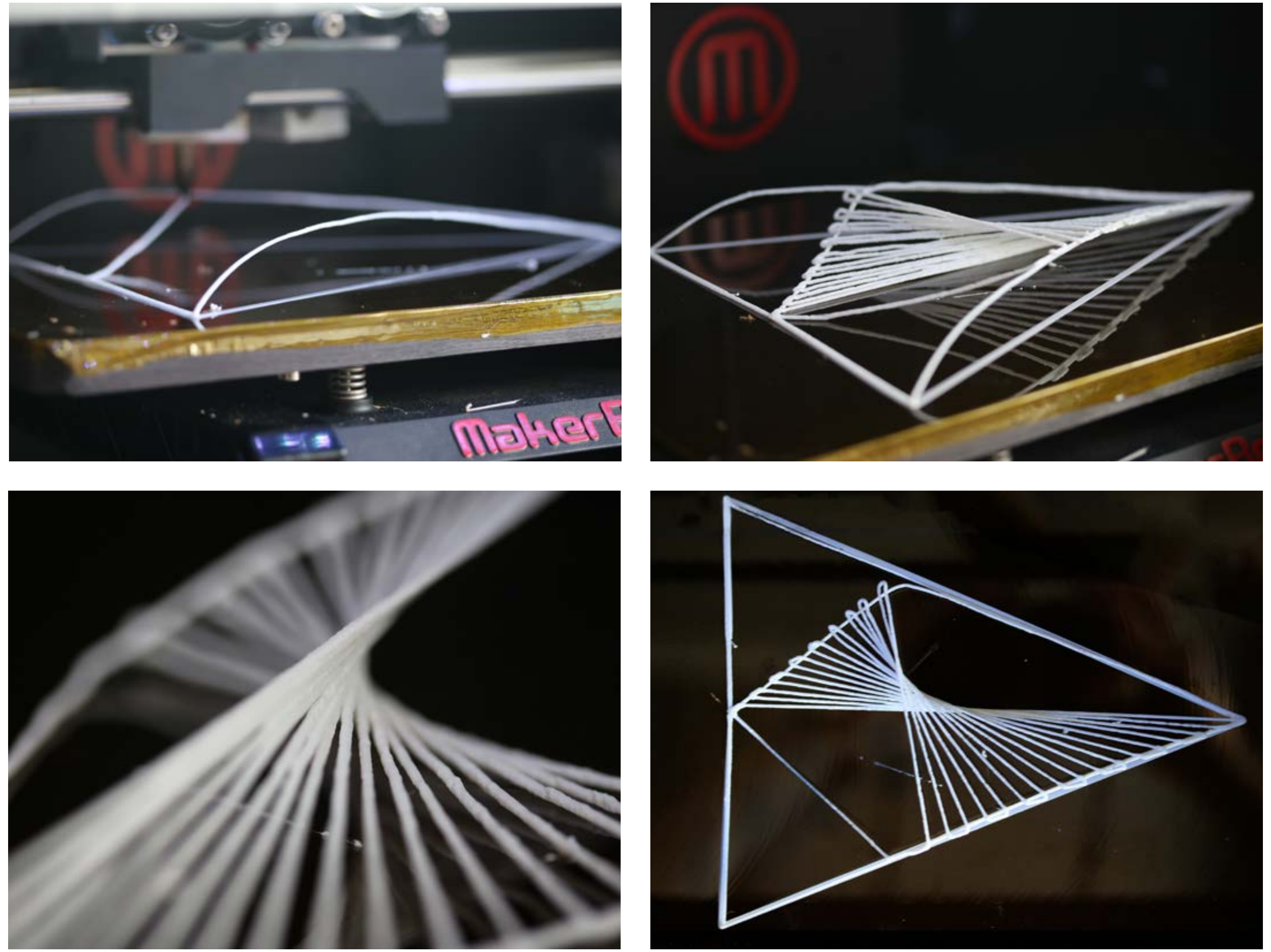
Print Time: 00:44:20
Material Used: 752mm White ABS
Nozzle : N2
Settings: N2 settings

Figure 54. Author, MBA Experiment 5



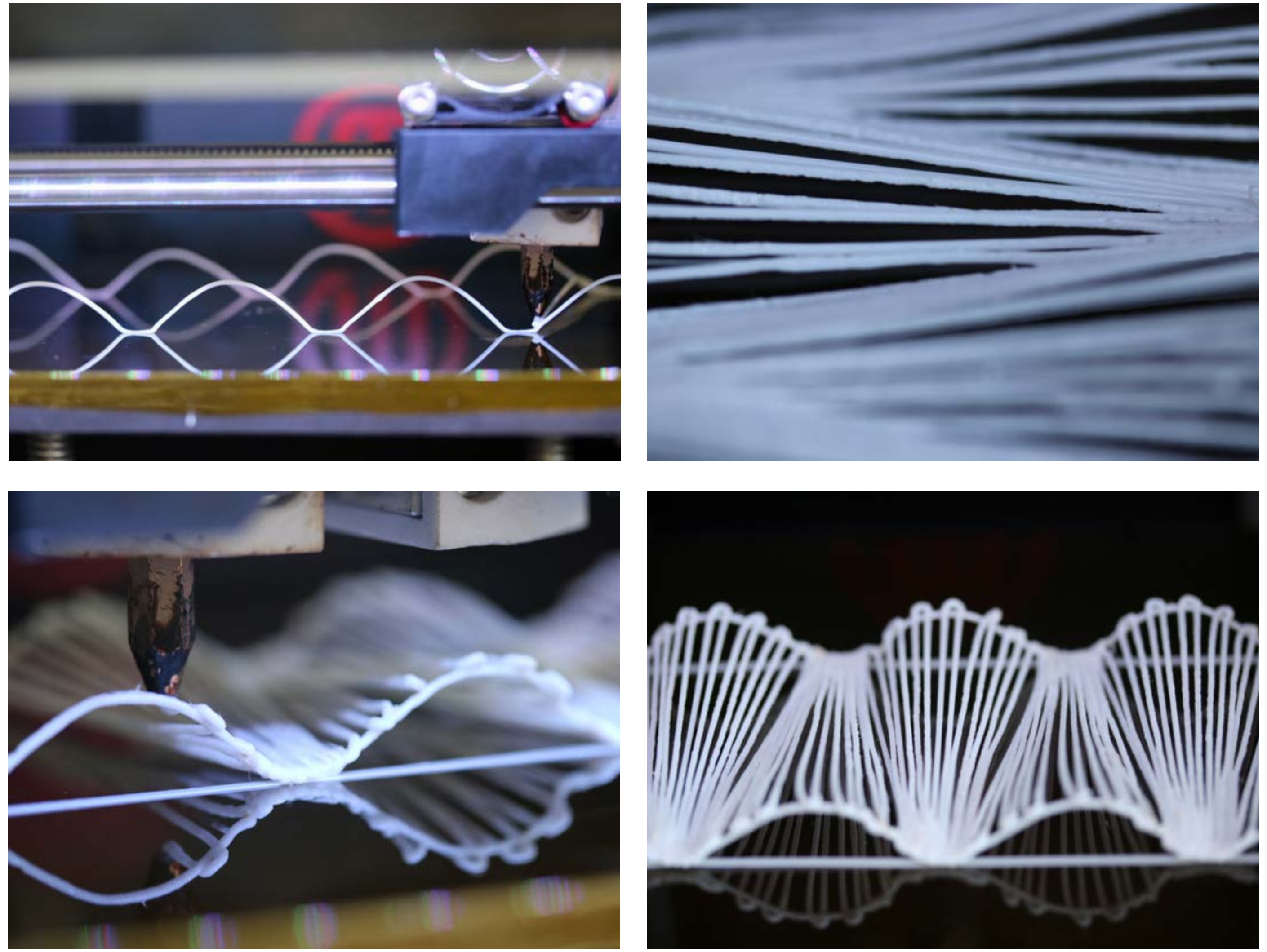
Print Time: 01.11.41
Material Used: 1780mm White ABS
Nozzle : N2
Settings: N2 settings

Figure 55. Author, MBA Experiment 6



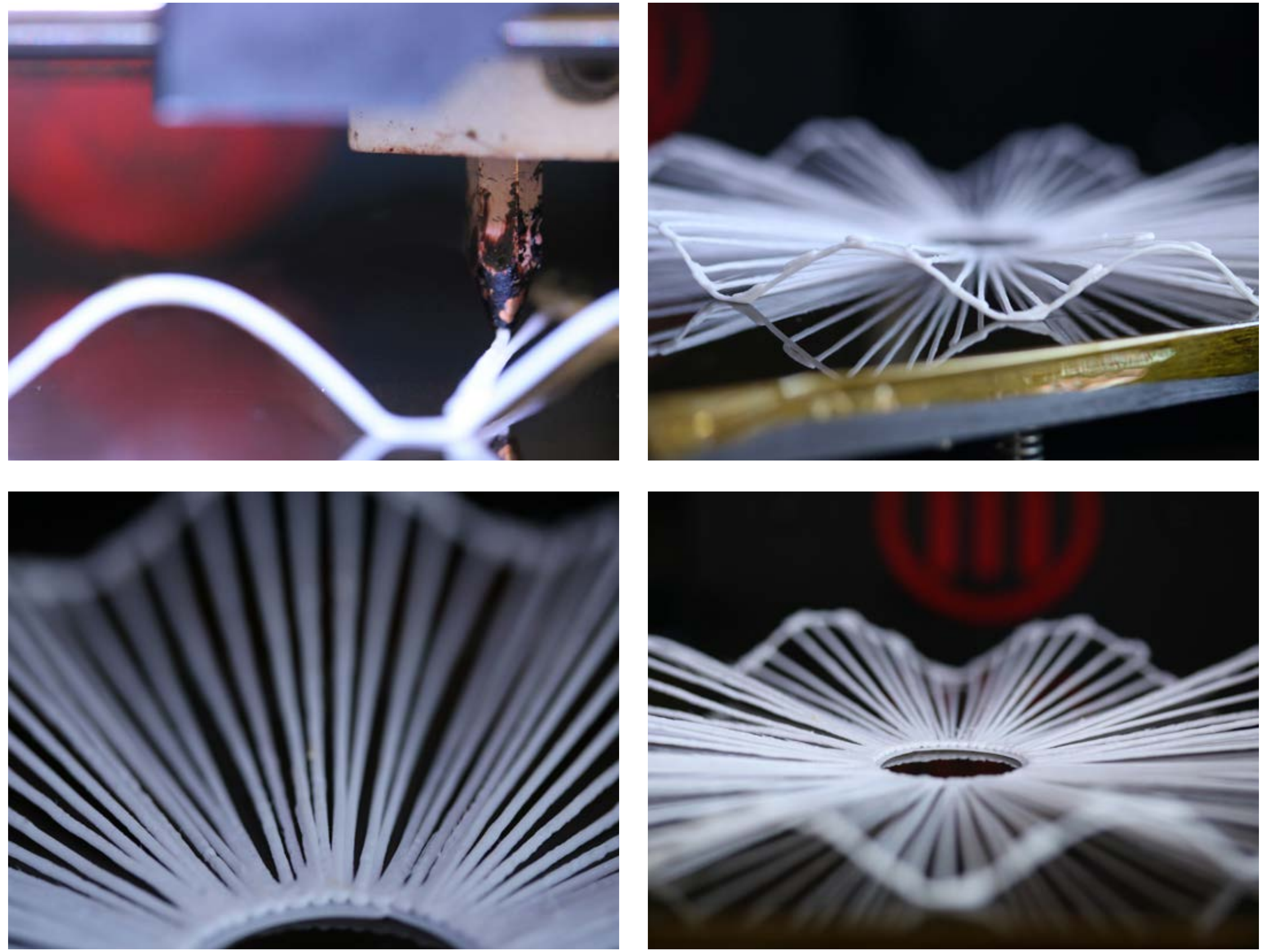
Print Time: 00:32:32
Material Used: 855mm White ABS
Nozzle : N2
Settings: N2 settings

Figure 56. Author, MBA Experiment 7



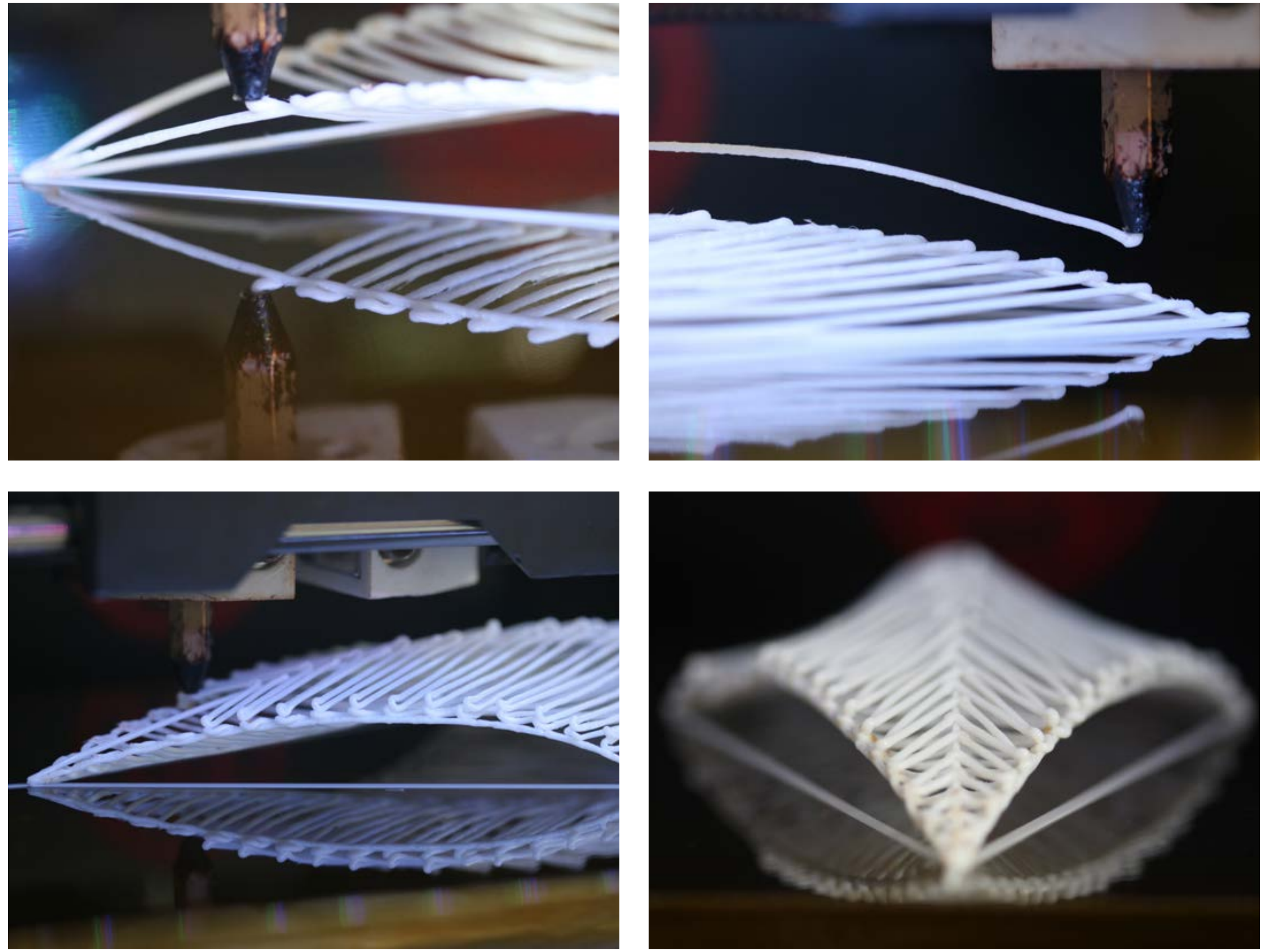
Print Time: 01.12.16
Material Used: 1800mm White ABS
Nozzle : N2
Settings: N2 settings

Figure 57. Author, MBA Experiment 8



Print Time: 01:15:16
Material Used: 1972mm White ABS
Nozzle : N2
Settings: N2 settings

Figure 58. Author, MBA Experiment 9



Print Time: 01.27.37
Material Used: 1578mm White ABS
Nozzle : N2
Settings: N2 settings

MINIMAL BASE ADHERENCE - SERIES FINDINGS

OPPORTUNITIES:

- General ability to dismiss the need to rely to flat base structures to build from, or build up large amounts of support material to do so

- Ability to print largely curvilinear and overhanging geometries

- Ability to widely disregard of rafts or base structures

- Development of modelling techniques without aid of surfaces or solids

- Ability to print some undercutting forms without use of layer-based systems

- Minimal material use and print motions for relatively complex forms

LIMITATIONS:

- Some extra material deposition required beyond intended form

- Difficulty in defining forms that stop in air (not on to printer bed or existing geometry) as the script has no extrusion stop/start definition

- Curves are least reliable when they have sharp geometries in the X and Y axis and print in space. Curves planar in Z space more reliable

- Necessity to get tolerance between sections of deposition close to ensure proper adherence between printed sections

SERIES 2: DYNAMIC LAYERING (DNL)

While this research seeks to no longer depend on built up planar layers, there became potential for interesting outcomes when 'layered' structures are formed with three-dimensional consideration and variable qualities. This series sought to pursue the opportunities arisen from structures built through combinations of accumulative layers and spatial deposition. This premise references back to base-up building techniques, but with toolpaths that consider the proposed form responsive method (FRM). Overall form and material were defined concurrently. DNL tests to discover a range of printing techniques to become applicable for variable properties, materiality and aesthetics. Such as in exploring how these 'layers' can be impacted by the spaces or interactions between sections of material.

Figure 59 expresses the main Grasshopper script used to create the DNL series models. Based off simple curves and rotational copies (called polar arrays), the fairly simple script allows for seemingly complex geometries to explore dynamic layering techniques through.

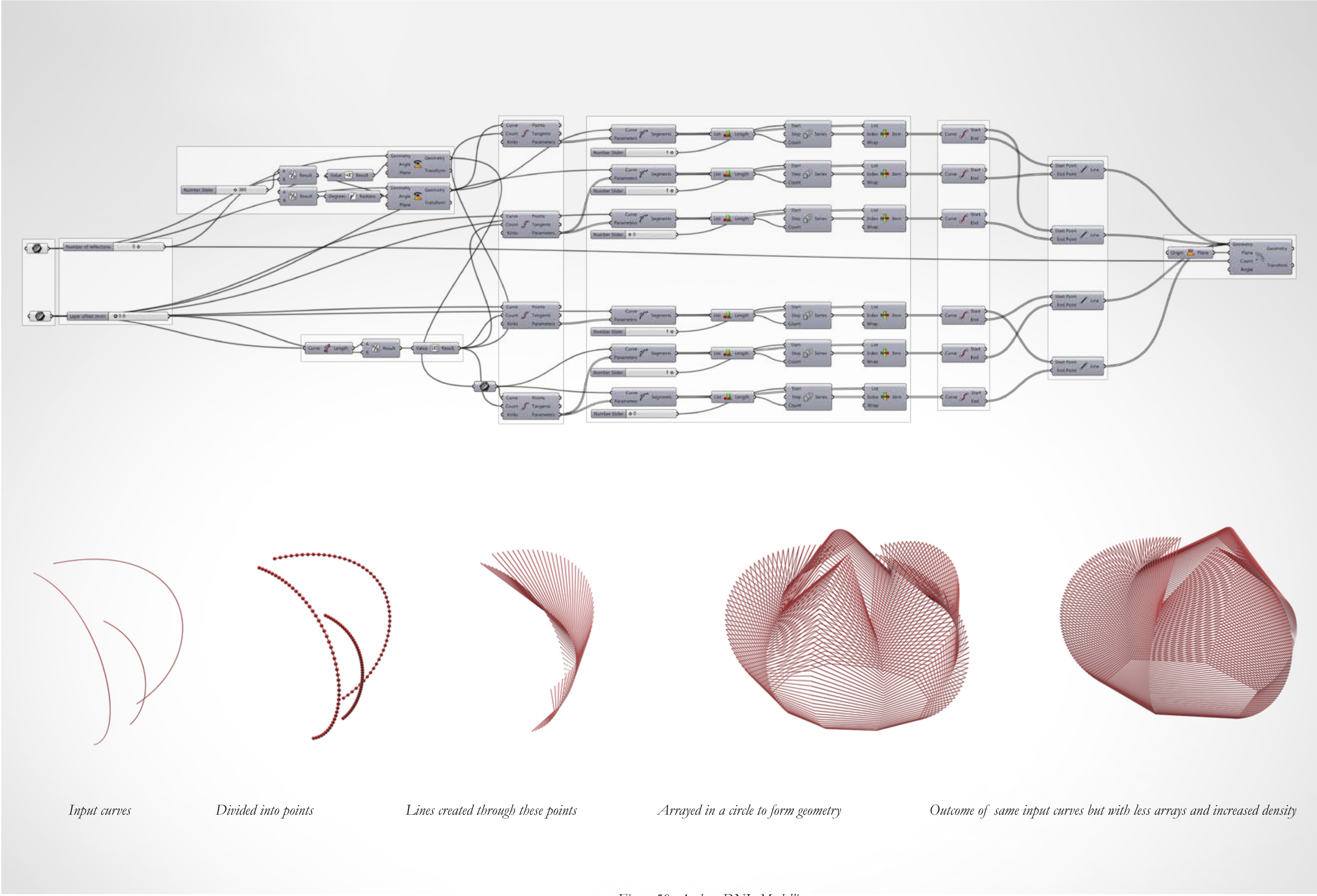
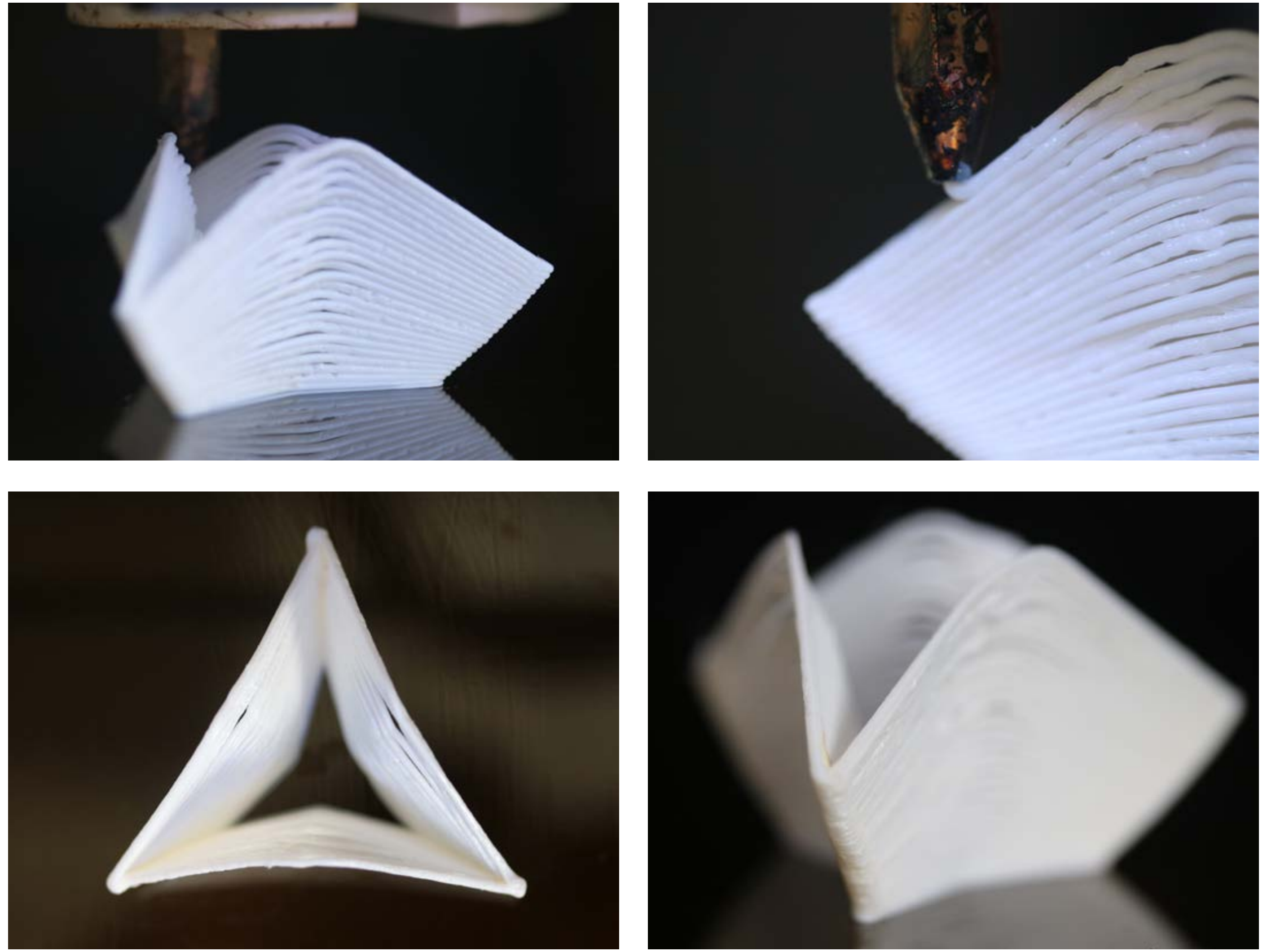


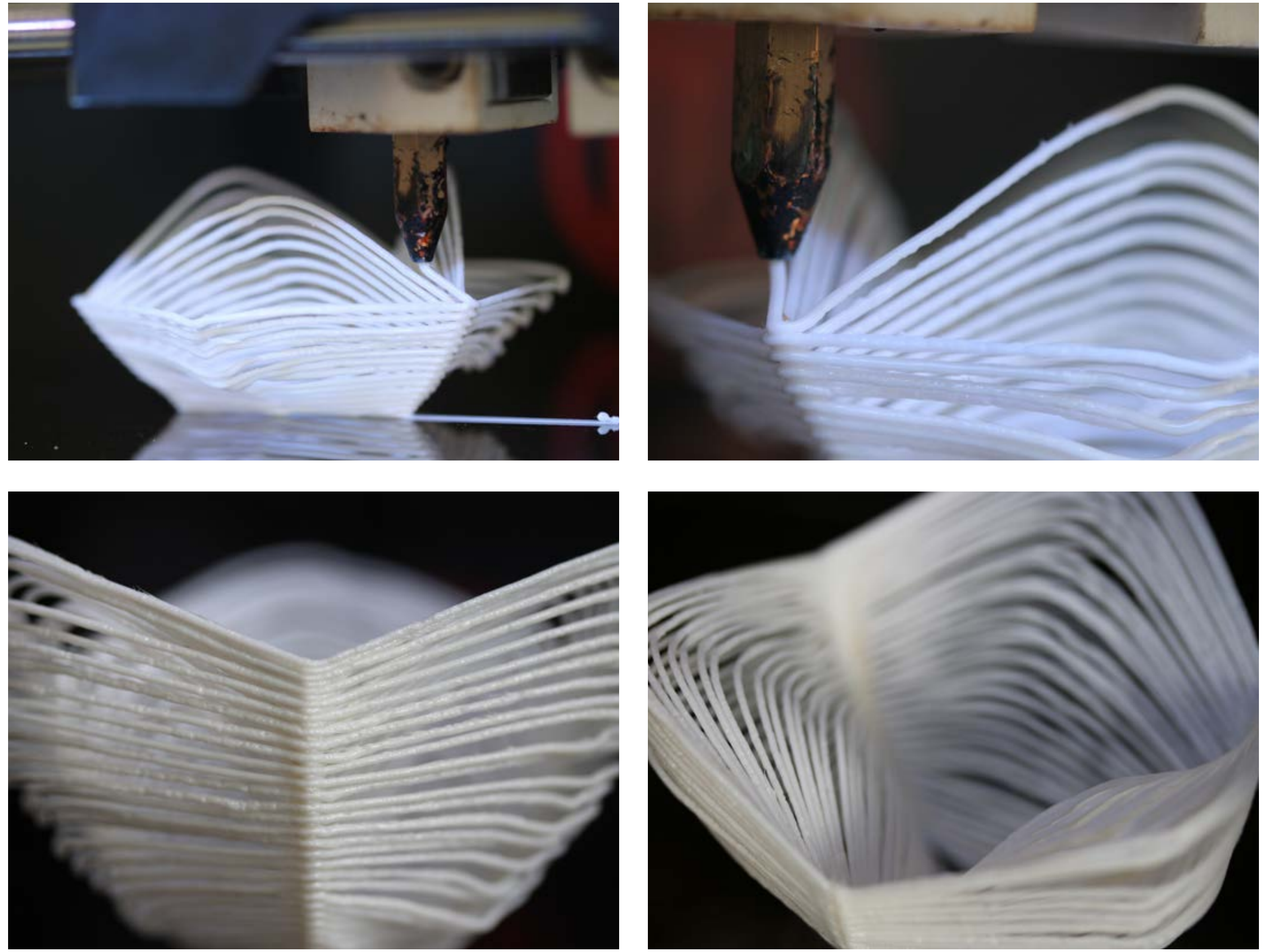
Figure 59. Author, DNL Modelling

Figure 60. Author, DNL Experiment 1



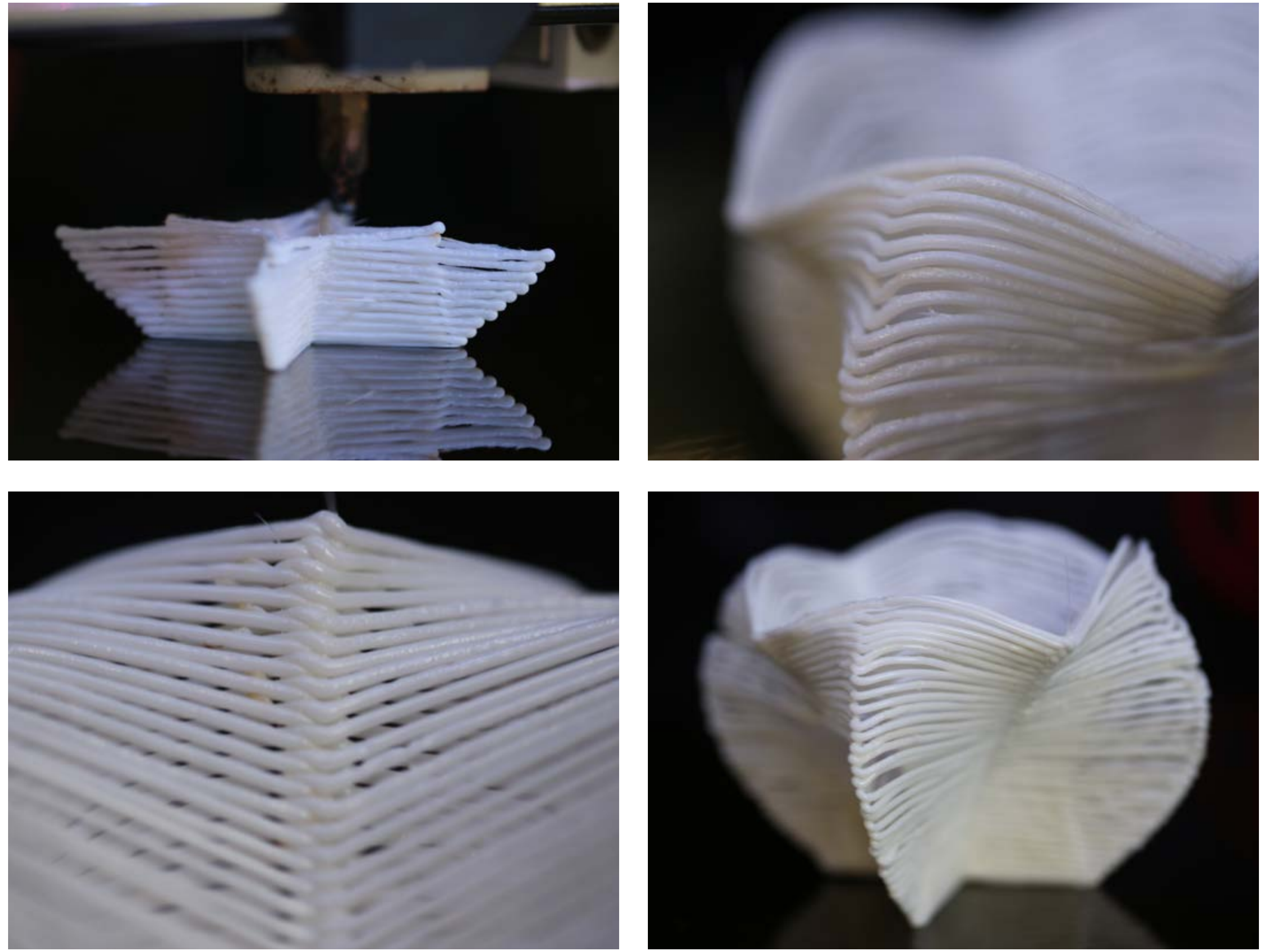
Print Time: 01:24:08
Material Used: 1242mm White ABS
Nozzle : N2
Settings: N2 settings

Figure 61. Author, DNL Experiment 2



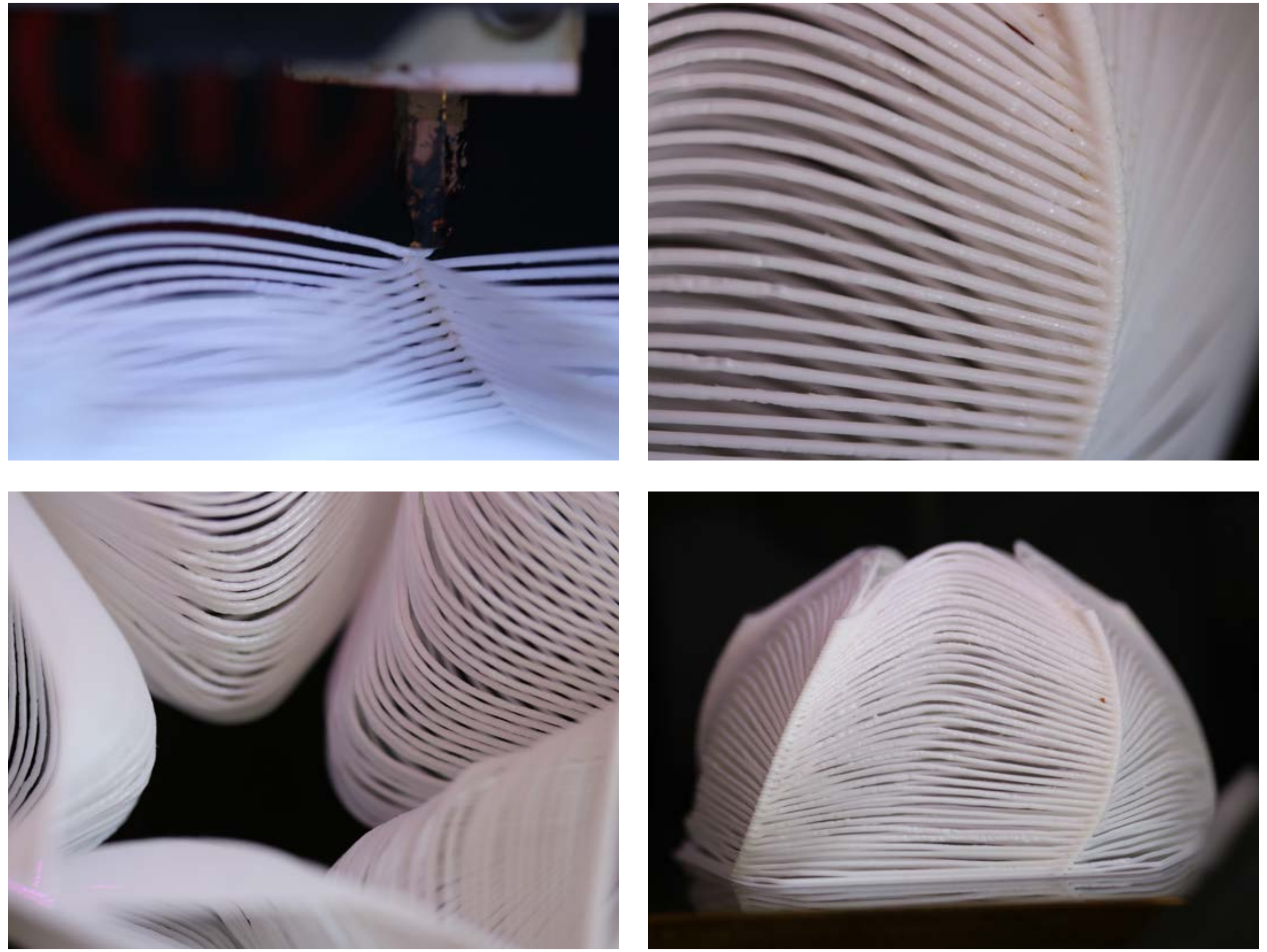
Print Time: 02:08:51
Material Used: 2105mm White ABS
Nozzle : N2
Settings: N2 settings

Figure 62. Author, DNL Experiment 3



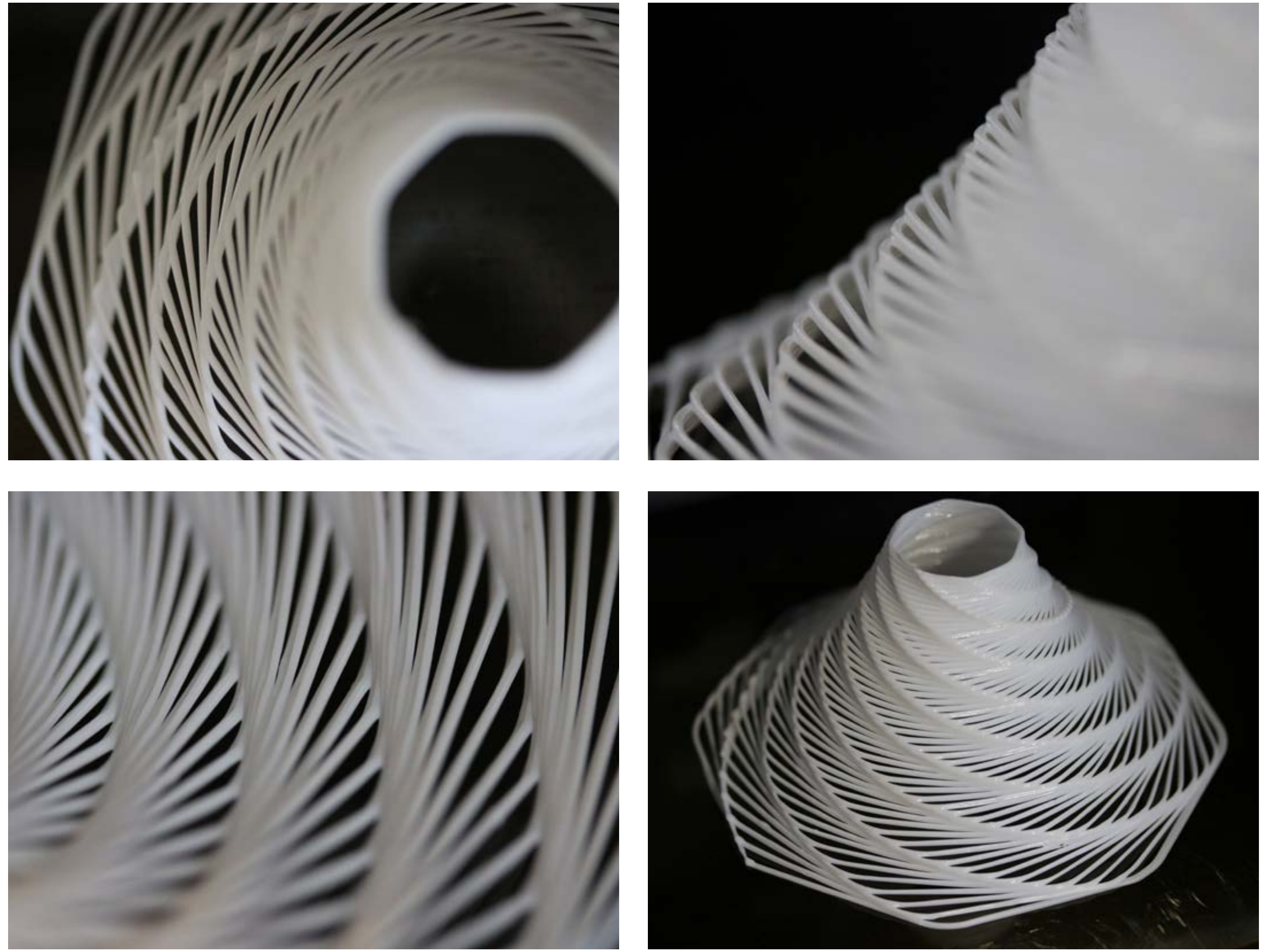
Print Time: 02.15.22
Material Used: 2203mm White ABS
Nozzle : N2
Settings: N2 settings

Figure 63. Author, DNL Experiment 4



Print Time: 04.02.16
Material Used: 3908mm White ABS
Nozzle : N2
Settings: N2 settings

Figure 64. Author, DNL Experiment 5



Print Time: 00.28:55
Material Used: 5086mm White ABS
Nozzle : N2
Settings: N2 settings

DYNAMIC LAYERING - SERIES FINDINGS

OPPORTUNITIES:

- Broader possibilities of layering when considered spatially

- Sense of reliability regained though building solely ground-up

- Contrast between highly spatial and dense layered areas creates interesting visual and structural qualities

- Dense areas gain structural integrity

- Open layers often creating spring-like quality

- Intricate patterns found at interaction of layers

- Taller forms can be made if building ground-up

- Even when printing in planar layers new qualities can be found through designing deposition, such as seen in DNL Experiment 5 (Figure 64)

LIMITATIONS:

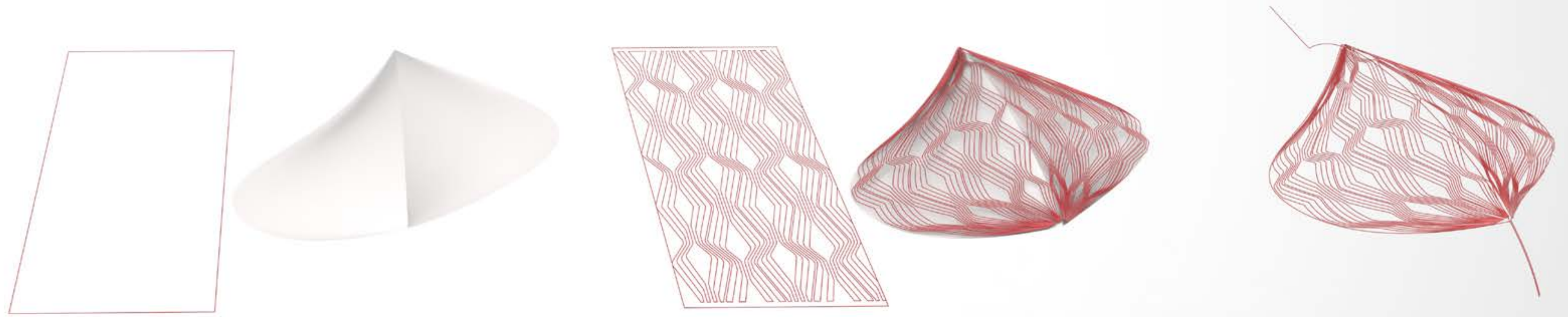
- More delicate tolerances. If any defined point of contact was not fulfilled the rest of the print became compromised

- Being strictly an accumulative process, portions of the prints were restricted by the needed offset from the previous layer, so a defined point needed to reach to build from, causing for geometric restrictions

- Largely Increased time and material usage

SERIES 3 : STRUCTURES, PATTERNS AND TECTONICS (SPT)

SPT sought to test the impact of surface patterning on material integrity, with focus towards influence on structure. It was explored how direction, interaction, and density impact the structural or mechanical qualities of a print. Tectonics and aesthetics were considered with influence from form. Underlying geometries throughout the SPT series are mostly consistent, letting pattern and structure be the focus of difference between experiments.



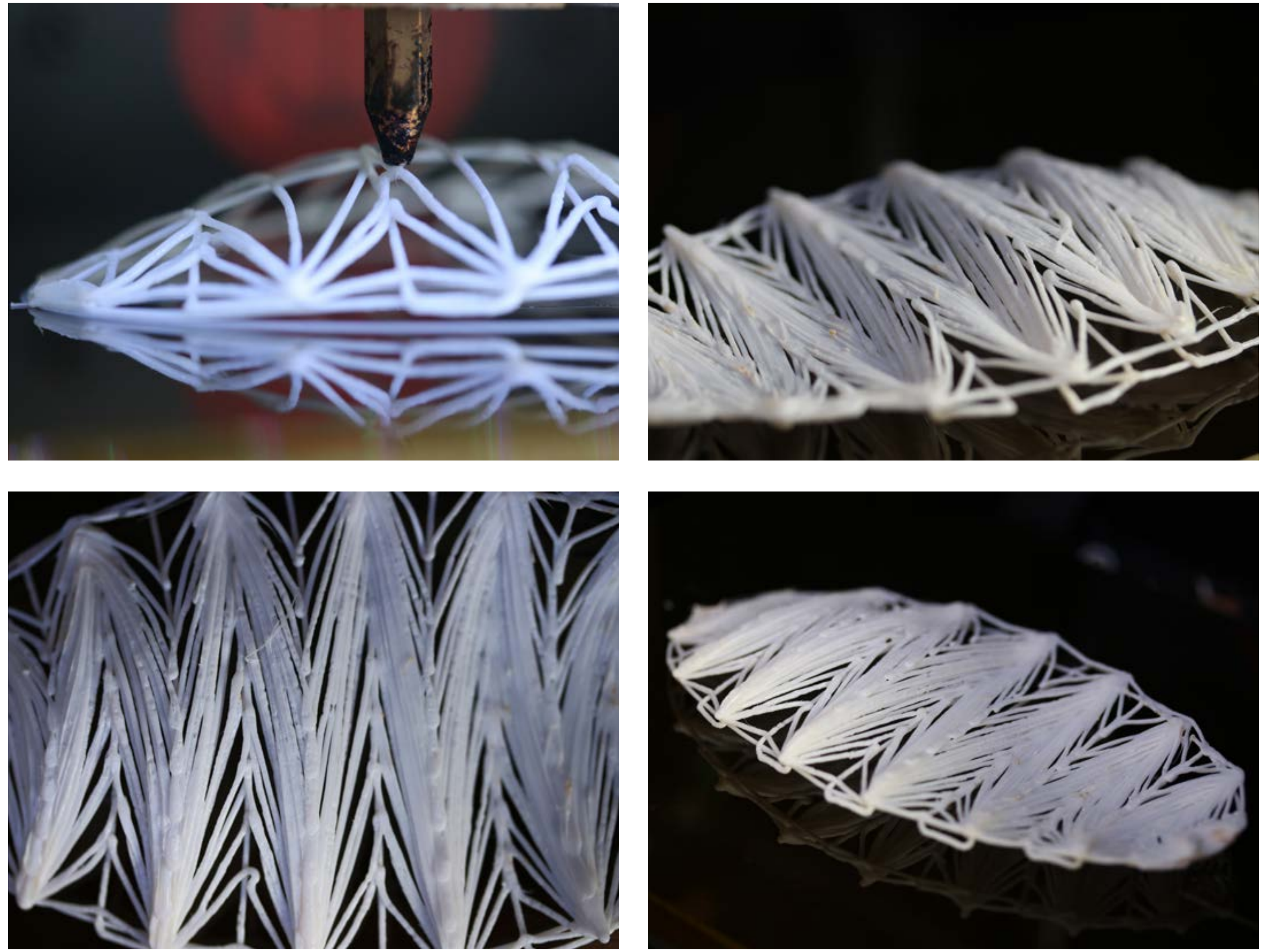
A surface is defined and run through a 'create UV curve' command to extract simple, flat dimensions

The desired pattern is created within this area, which is then 'flowed along surface'.

Curves are edited to include any extra motions or needed extrusions.

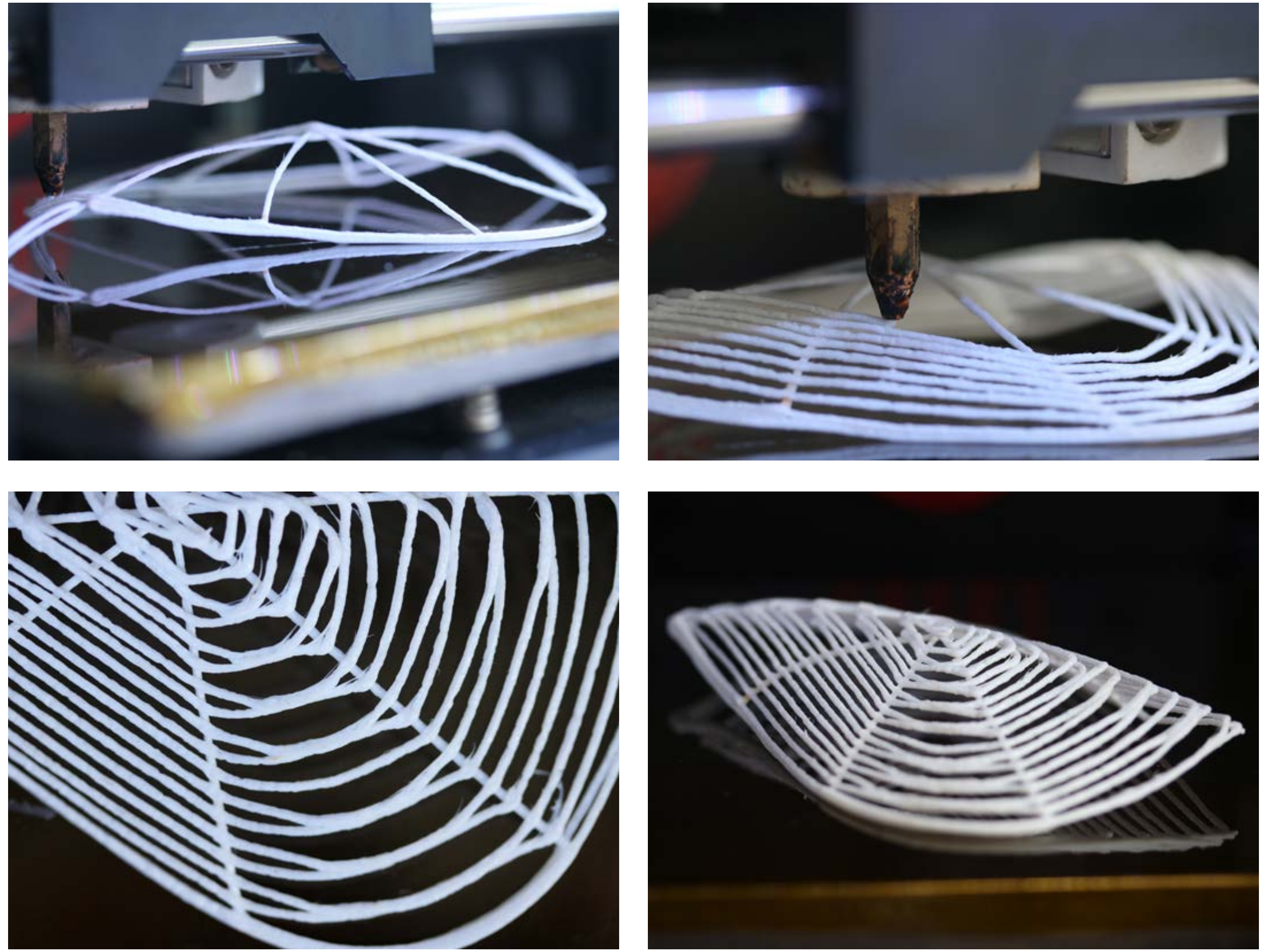
Figure 65. SPT Modelling

Figure 66. Author, SPT Experiment 1



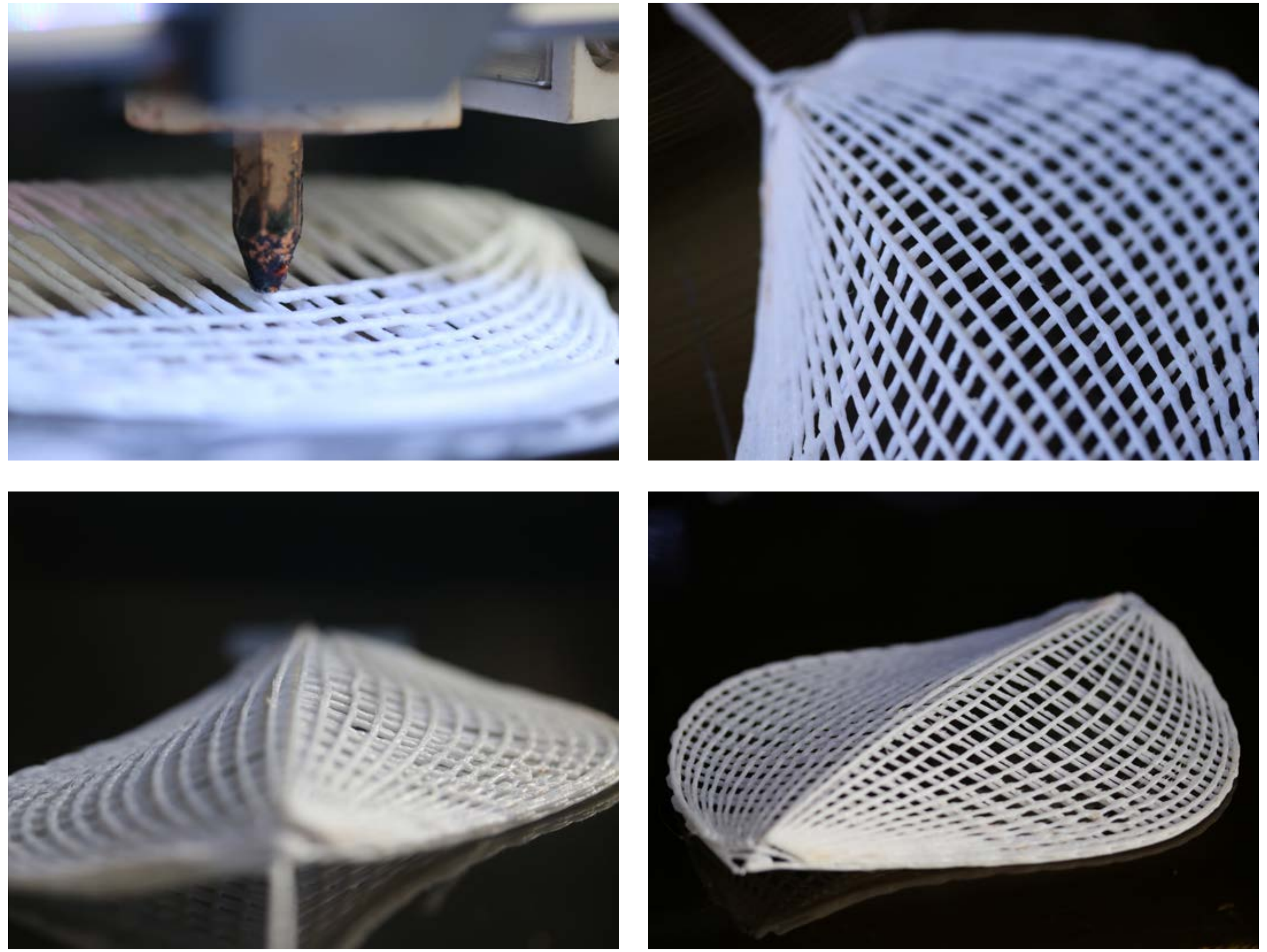
Print Time: 02.01:21
Material Used: 3101mm White ABS
Nozzle : N2
Settings: N2 settings

Figure 67. SPT Experiment 2



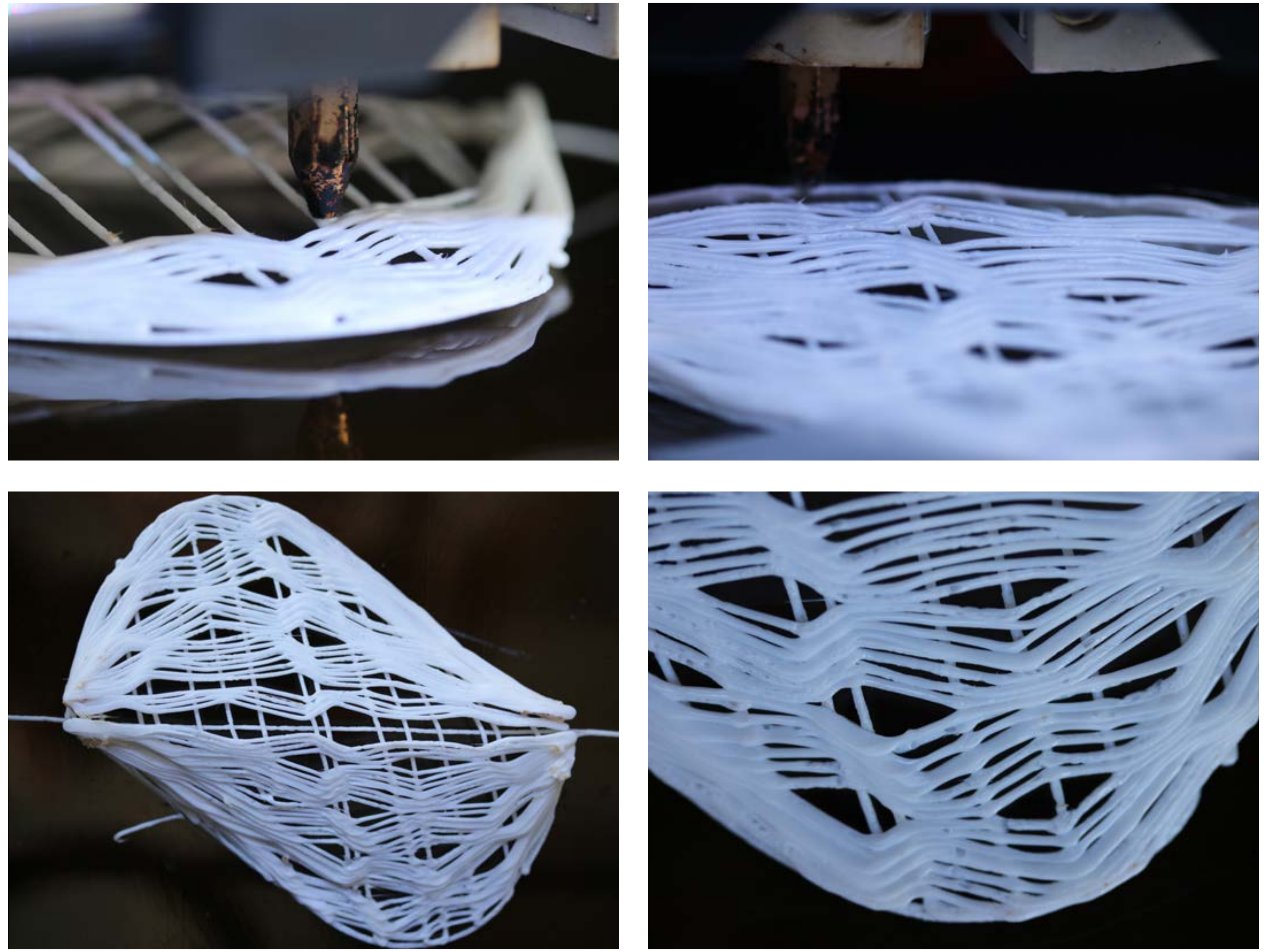
Print Time: 00.43:08
Material Used:702mm White ABS
Nozzle : N2
Settings: N2 settings

Figure 68. Author, SPT Experiment 3



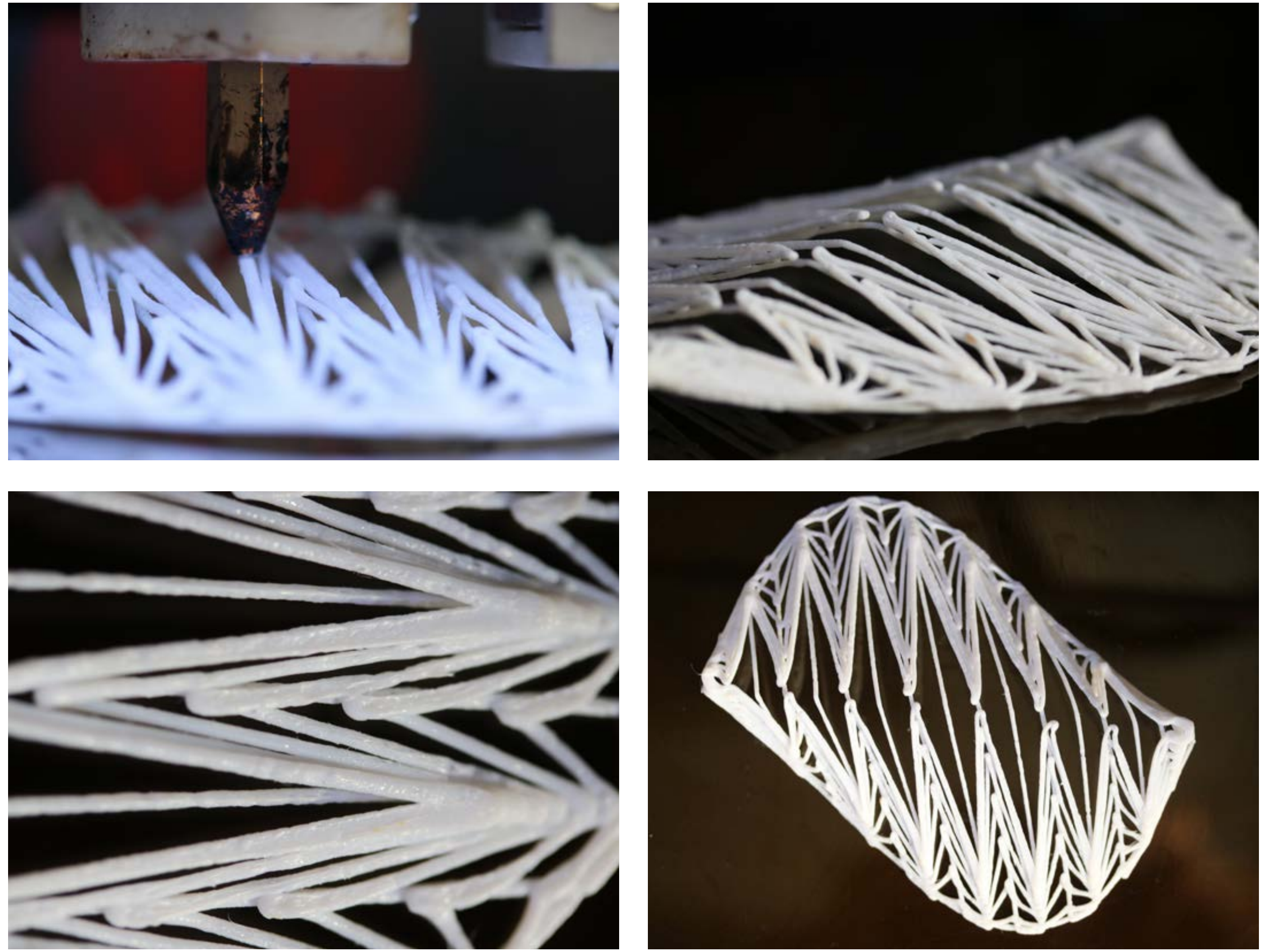
Print Time: 01:14:11
Material Used: 1211mm White ABS
Nozzle : N2
Settings: N2 settings

Figure 69. Author, SPT Experiment 4



Print Time: 01:55:20
Material Used: 1880mm White ABS
Nozzle : N2
Settings: N2 settings

Figure 70. Author, SPT Experiment 3



Print Time: 01:32:13
Material Used: 1504mm White ABS
Nozzle : N2
Settings: N2 settings

STRUCTURES, PATTERNS AND TECTONICS - SERIES FINDINGS

OPPORTUNITIES:

- Affirmation of the large impact that material deposition has on structural integrity. Direction, density, form and format impacting materiality

- Material built largely in one direction caused for directional bend. Such as in SPT Experiment 3, which has large bending flexibility in one axis as opposed to the perpendicular axis

- Overlaid material directions gain great strength

- Spiral structure creates spring-like qualities

- Visual patterning as a cue for interaction and materiality

-More room for exploration when exploring structures, patterns and tectonics in relationship to specific design requirements

LIMITATIONS:

- The main difficulty becomes the negotiation of structural, aesthetic, tectonic and other factors impacting how material can be deposited. As well as considering these with overall form, product requirements and physical limitations, designer becomes an important mediator of prevailing factors

Figure 71. Author, Abstract Design Experiments

ABSTRACT EXPERIMENTS FINDINGS

OPPORTUNITIES:

These experiments began to express how simple, bespoke processes can create new material qualities through freeform 3D printing. Many specific qualities were found in the experiments, and the integration of these will be used to further increase opportunity for Designed Deposition. More general opportunities exposed were;

- The ability to create variable material qualities, both locally within a single print, and over sperate artefacts

- Freedom to define materiality and tectonics for specific purposes

- Largely diminished need for support material and less wastage of material

- Greater control over visual, physical and tectonic impact of material deposition

- Ability to efficiently create open or mesh-like structures. (Compared to traditional FDM printing)

- Visual patterning as a cue for the artefacts use and structural integrity

LIMITATIONS:

A range of limitations or needed considerations became exposed. These were primarily;

-Base adherence. While the MBA series proved it possible to create structures with very little base contact, It becomes very crucial that this adheres and does not lift, so initial portions of a print must be highly considered

-Small amounts of drooping and directional pull were still evident. These will continue to be ongoingly tweaked

- Restriction of undulation before obstructing printed geometries with the extruder and printer components

- Need to start extrusion early, i.e. add an extra length onto the beginning of the toolpath, to give time for the material to make its way through the extended nozzle before the printing of critical parts of structure is attempted

-The inability to define stopping at starting material extrusion. To compensate, consideration to the design of non-printed motions and movement between intended geometry becomes a large consideration. These could either be designed into the artefact or be printed and later trimmed

PART 3

APPLICATION

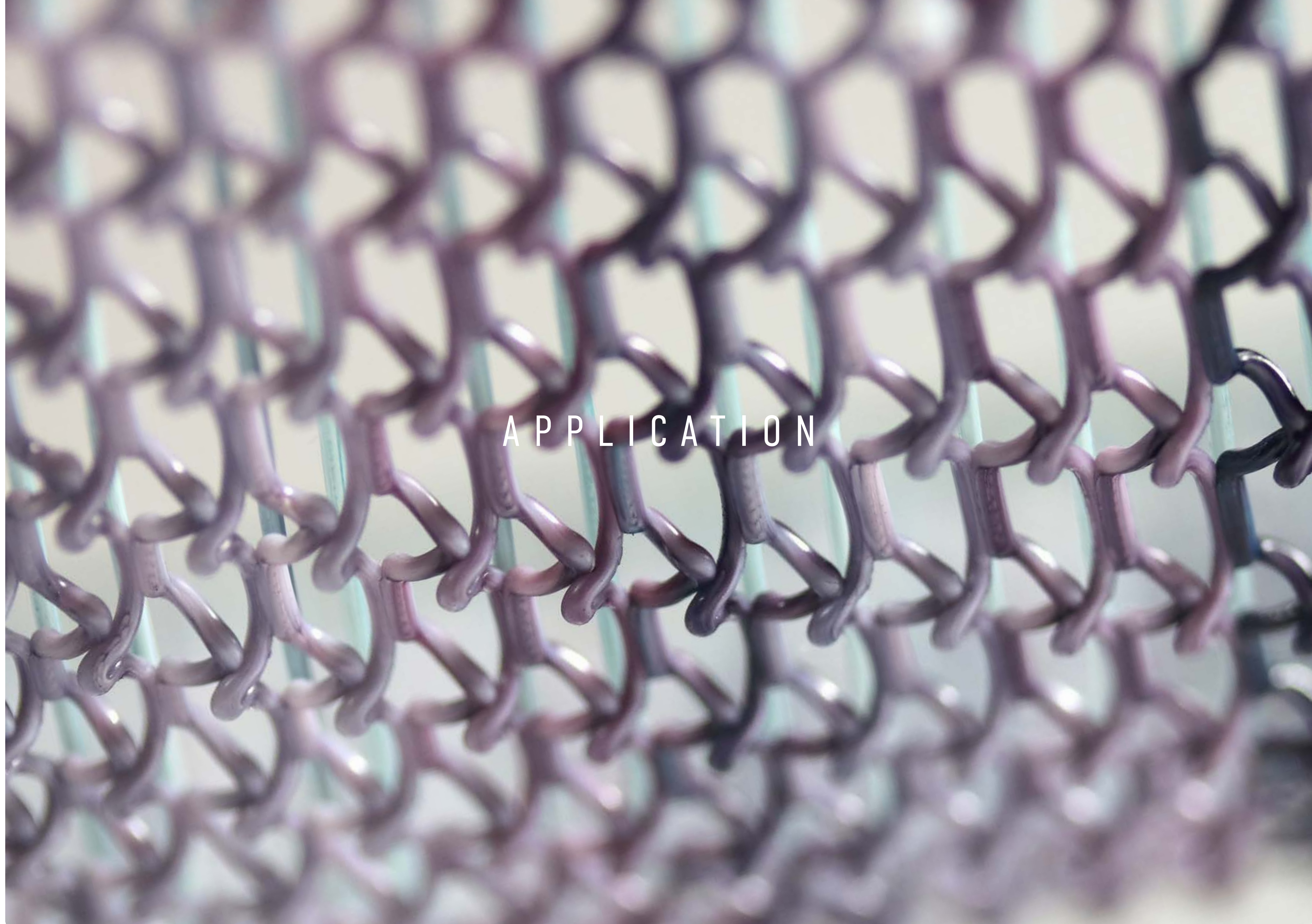


Figure 72. Author, Machine Adaptation Bits and Peices

3.1 - MACHINE ADAPTATION, COMPUTATIONAL DEVELOPMENT AND SETTINGS TESTS: MENDELMAX

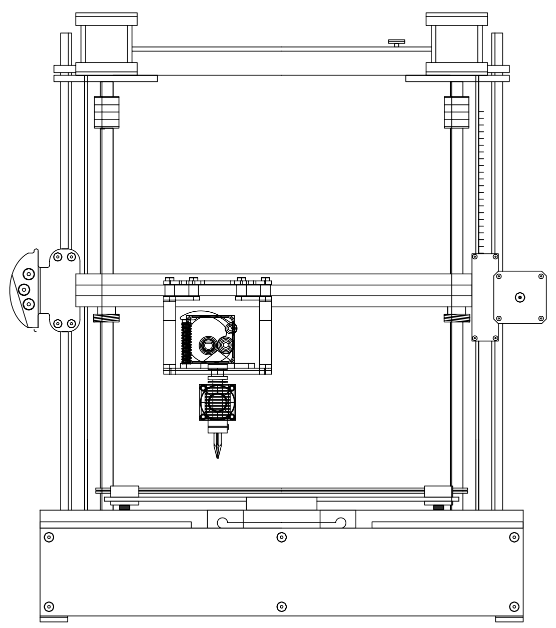
After the experimentation phase (Part 2) the requirements and abilities of the spatial printing process when using standard FDM printers were more intimately understood. In response to the gained knowledge, machine and computational systems were updated and new tests undergone. This process was much more efficient and straightforward, as the systems and processes allowing for successful freeform printing were now understood and already in place. The developments taken place included;

- Gaining a new FDM printer, and understanding its unique requirements both physically and computationally

- Producing new iterations of custom nozzles that were increasingly appropriate for freeform processes, informed by the findings of Part 2, and updating extrusion settings accordingly

- Updating the computational processes for the creation of G-code from an input curve/toolpath with increased ease and added functionalities.

MACHINE ADAPTATION - MENDELMAX

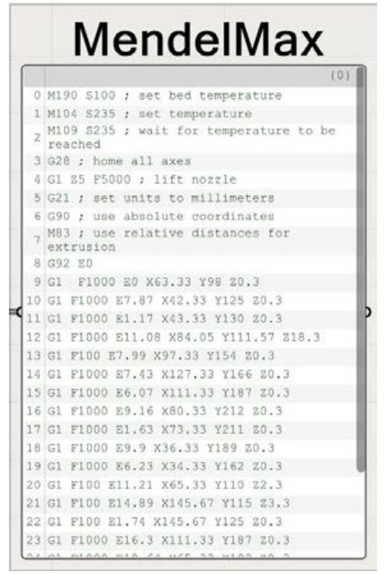


MendelMax

Figure 73. Author, MendalMax Illustration

A MendalMax was acquired and used for the remaining duration of the research. This FDM printer originally comes as a RepRap kit set, so is a highly customisable printing resource. The extrusion head was mounted to become slimmer and extend further below x axis gantry to allow for more z axis freedom without the print head hitting existing printed areas. Overall, the printer allowed for larger geometric freedom and was found to be more reliable than the Makerbot Replicator 2X.

G-CODE TO PRINT



G-code from Grasshopper/ Silkworm

Pasted into Notepad++ and saved as a .gcode file

Figure 74. Author, G-code to Print MendalMax

G-code was copied from Grasshopper into notepad++ to be formatted as a .gcode file. The printer was controlled through the software Repetier, where G-code was loaded, and printing was controlled.

Figure 75. Author, N3 and N4 Settings Adjustments

SETTINGS ADJUSTMENTS - NOZZLE 3 (N3) and NOZZLE 4 (N4)

Informed by how the previous nozzles performed (N1 and N2) during the experimentation phase, new iterations of the nozzles were developed. These new nozzles were increased in nozzle angle, to allow for extrusion in tighter spaces and at greater angles. Length was pushed further to test limits, and smaller nozzle extrusion diameters were explored for slightly finer print strands. Thorough settings tests were no longer required, as the grasshopper script was set up with adjustable parameters that could quickly edit line and extrusion relationships. These sliders were adjusted iteratively until appropriate settings became established. Many of test prints are seen in Figure 75.

Nozzle 3 (N3) - Increased overall dimension, greater angle of extrusion tip, and decreased extrusion hole diameter.

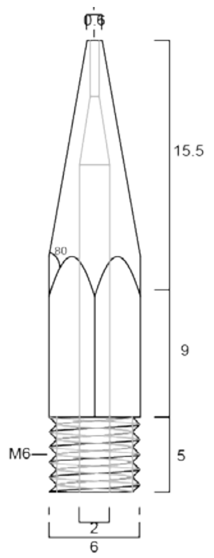


Figure 76. Author, N3 Dimensions

It was found that Nozzle 3's largely increased length was just beyond the limitations for successful freeform printing in the manner developed. A large amount of prints with iteration of the settings parameters were created, but no prints were fully successful in their self-supporting abilities. Subsequently, the nozzle was abandoned and a new nozzle iteration (N4) created.

Nozzle 4 (N4) - Reduced overall body length that N3. Slight adjustments of extrusion angle and extrusion hole diameter.

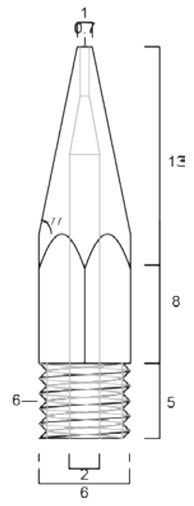


Figure 77. Author, N4 Dimensions

Nozzle 4 was tested and the settings were adjusted, to eventually find suitable print settings. These settings were;

For flat movments;
Extrusion rate = Line length x 0.23
Printer speed = F1000

For spatial movements;
Extrusion rate (UP) = Line length x 0.185
Extrusion rate (Down) = Up Erate x 0.9
Printer speed = F1000

These will be referred to as the N4 Settings.

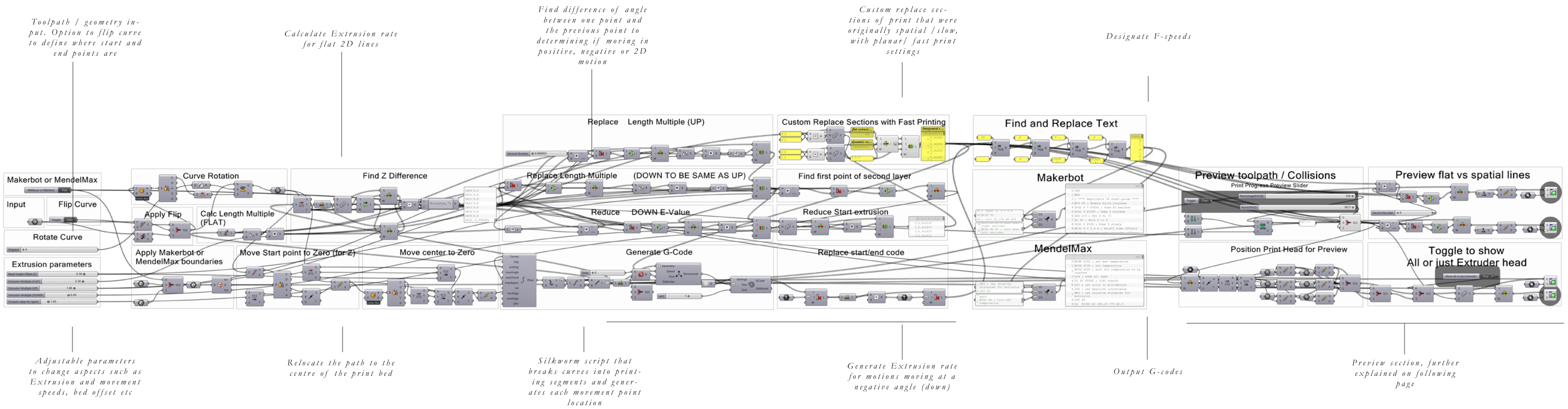
UPDATED GRASSHOPPER SCRIPT

The findings and knowledge gained from the experimentation stage were used to inform further developed the grasshopper script.

Below: Figure 78. Author, Grasshopper Script Iteration 2

The grasshopper script was developed to gain new features and streamline the process between toolpath delineation, and g-code output. The Script was developed to include features such as rotating the toolpath within the print area, and previewing and adjusting settings to be for printing on either the Makerbot or MendelMax.

The N4 Settings were input as adjustable parameters. These were often overwritten with custom settings depending on the desired qualities of a print.



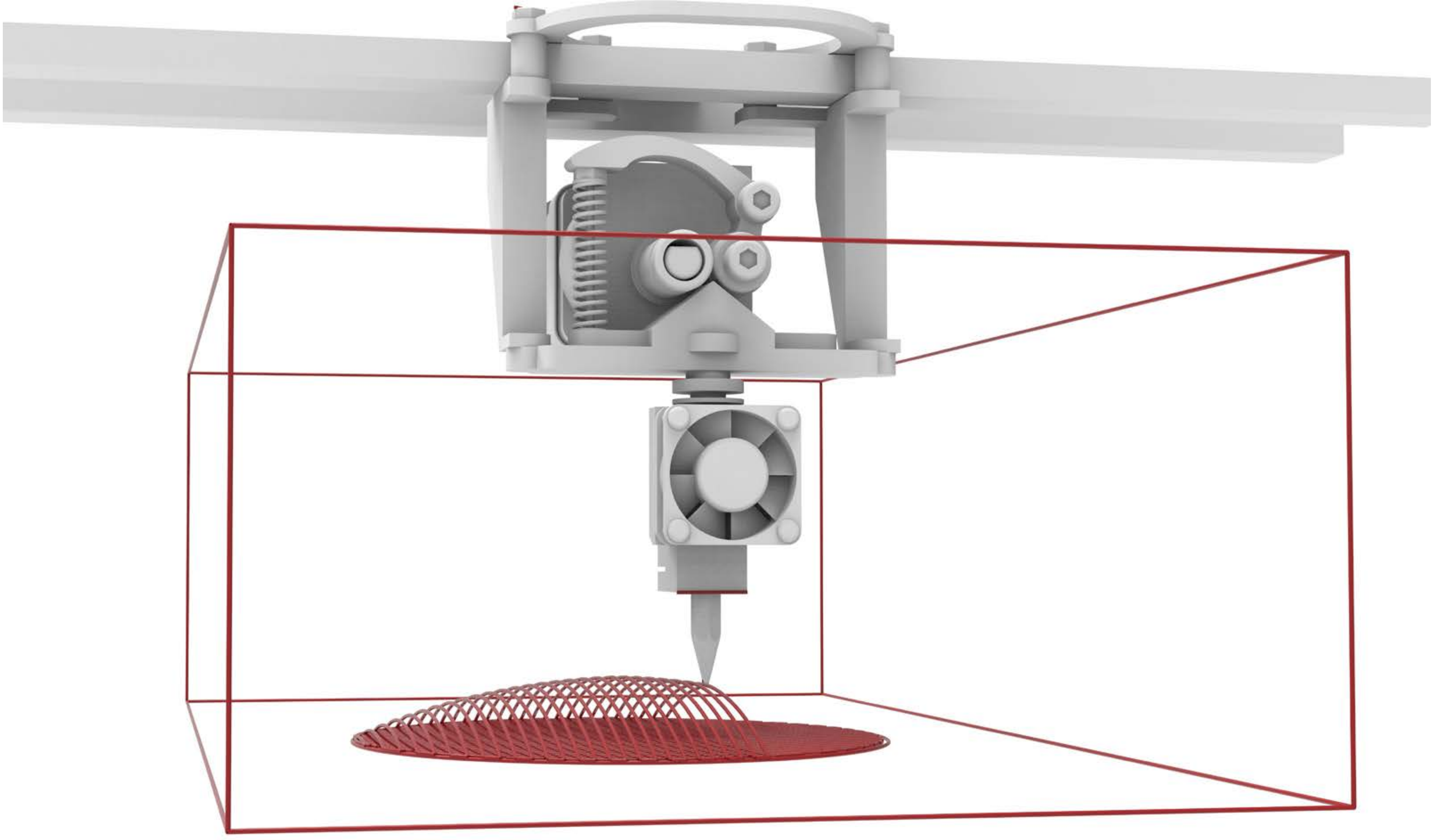


Figure 79. Author, MendelMax Toolpath Preview

SCRIPT UPDATE DETAILS

Some of the new additions to the Grasshopper script are shown below, seen in Figure 81. Most were in the realm of preview and locational adjustments that saved time, mainly in checking all aspects of a print prior to physical printing. One part that became largely useful was the previewing of the locations that planar or spatial settings were going to be used, as seen in Figure 80. The red lines expressing spatial print sections, and the grey planar. The new extrusion equipment of the MendelMax was modelled for the motion preview, as seen in Figure 79.

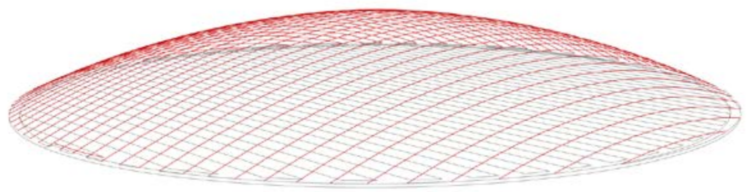


Figure 80. Author, Spatial vs Planar Line Preview

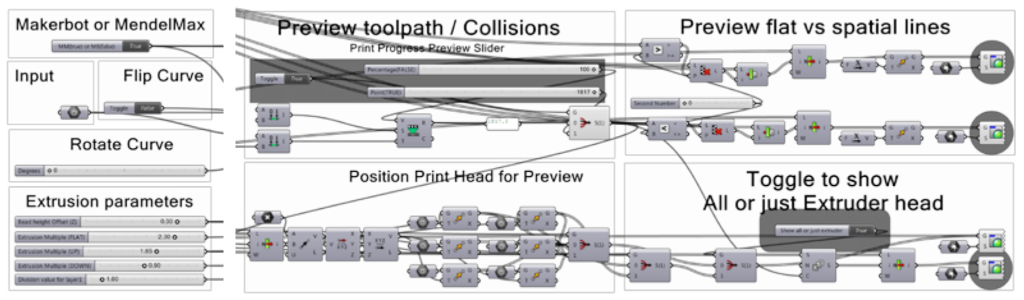


Figure 81. Author, Grasshopper Update Features

Figure 82. Author, Application Based Experiments

3.2 - APPLICATION BASED EXPERIMENTS

To further understand how freeform 3D printing could be embraced through an industrial design perspective, application based exemplars were developed through self-defined directions. Three unique directions were explored. These series sought to find how Designed Deposition and the form responsive method could be utilised for a range of industrial design focused uses, with response to specific design requirements. Among these were object, electronic, and furniture based explorations.

1.
Variable Density; Solidity and Open Structure Exploration;
Through Application Experiment 1; a 3 part Kitchen Utensil Set.

2.
Mechanical Use, Structural Diversity, and Ergonomic Customisation;
Through Application Experiment 2; a Computer Mouse, consisting of printed base and top sections, with externally sourced componentry.

3.
Parametric Patterning, Variable Density, Mass and Small-scale Customisation;
Through Application Experiment 3A and 3B; scale models of Mass Customisable Furniture.
Through Application Experiment 3C; a scale model of highly adjustable Custom Furniture.

Note:
- Red images indicate parametrically modelled designs
- Back images indicate directly modelled designs

Figure 83. Author, AE1 Printed Iteration

APPLICATION EXPERIMENT 1 (AE1)

Variable Density; Solidity and Open Structure Exploration Application Exemplar; Kitchen Utensil Set

By digitally crafting through curves as opposed to solid forms, material becomes controllable down to the single print strand. This exposes greater government of the formation of open structure, and its morph into solid geometry. This series sought to explore varying levels of structural dispersion and its potential applications. A three part Kitchen Utensil Set was chosen to explore this through. Each object within the set had unique requirements for density towards its intended use. The set was designed to be for cooking or baking contexts, which use varying arrangements of meshes, solids, and structures to impact interaction with substances. Within each piece of the set, there were local needs which structure was aimed to vary to attend to. Such as from a dense, strong handle, to a light, open mesh.

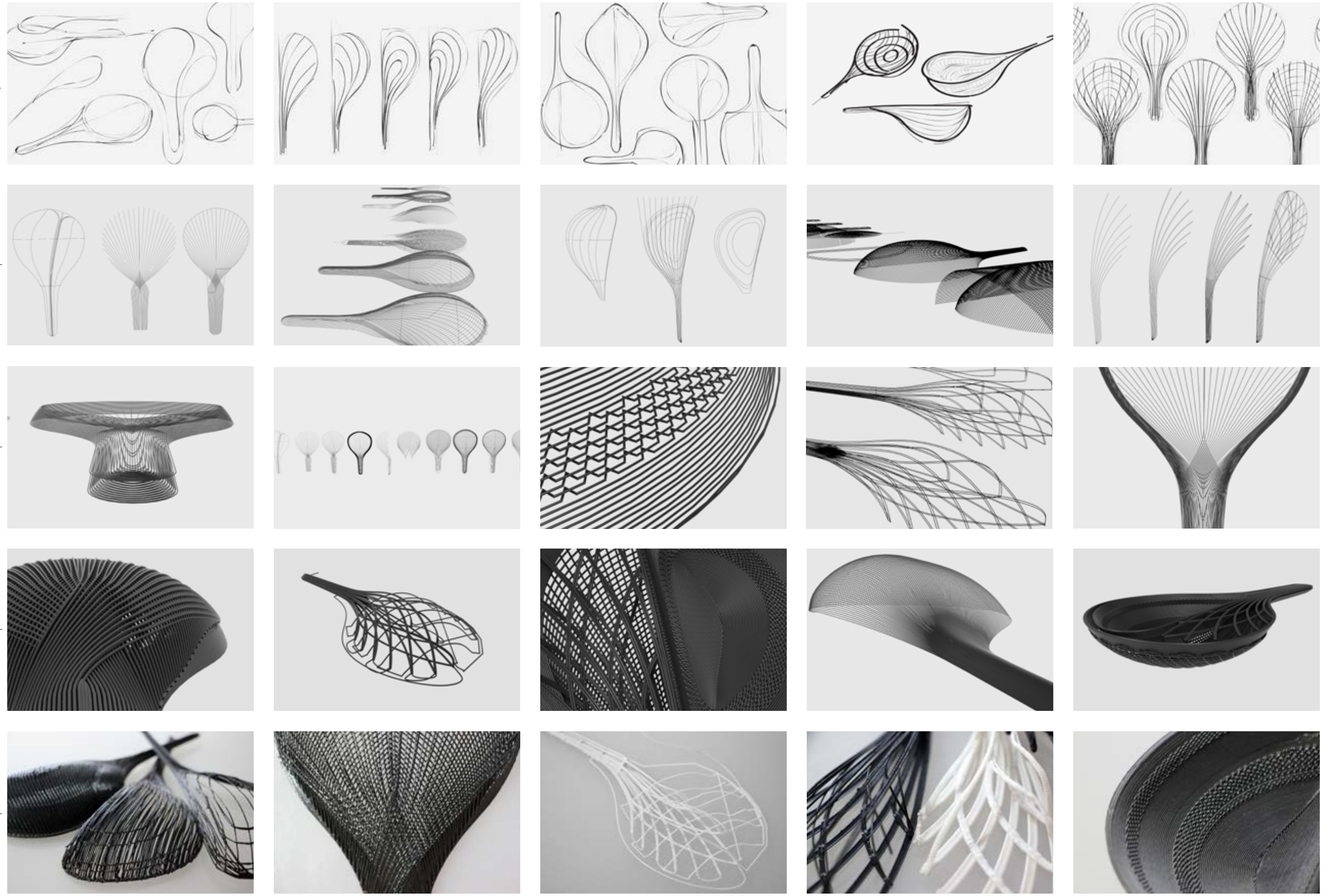


Figure 84. Author, AE1 Development Process

KITCHEN UTENSIL SET - DESIGN DEVELOPMENT

Below: Figure 85. (a-c) Author, AE1 Design Development

Measuring Spoon

Figure 85(a)

The measuring spoon application provided two primary initiatives; holding liquid and expressing volumetric measurement. The water-tight necessity presented a tricky brief for designing deposition as the most reliable solution came with resorting back to a layer based process. However, in being layer-based but three-dimensionally informed, layers could still be developed to become attentive to the underlying geometry. While most layers had to be built somewhat bottom-up up to guarantee water tightness, these could still be deposited through simultaneous x, y and z axes motions, avoiding harsh stair stepping occurrences at drastic overhangs. It was discovered that small patterning within the layers could still keep the object water tight, while allowing pattern and texture to express volumetric markers. This patterning was developed with inspiration from interesting layer interactions found in the Dynamic Layering series in Part 2.2.

Sieve

Figure 85(b)

The application of the sieve called for a small and consistent mesh structure, handle strength and decent volume mass for substances. The form allowed generous room for exploration of how to disperse material from solidity to open structure. The mesh structure required material deposition in alternating directions, and this patterning requirement developed brief for interesting aesthetic repercussions and overlayed material interactions. While the form and general arrangement developed quickly in response to needed geometry, a highly iterative development phase was necessary to establish all offset and pattern layers within suitable tolerances of each other.

Whisk

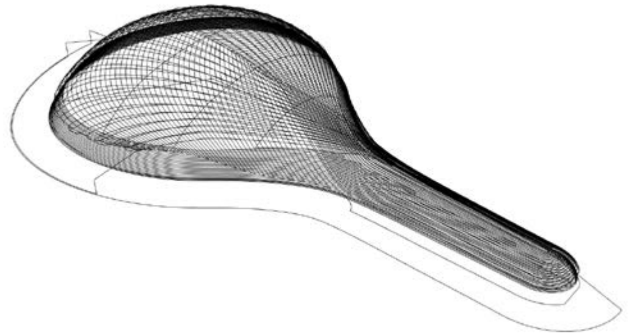
Figure 85(c)

Open, flexible, and strong framework were the primary requisites for the whisks configuration. The freeform printing process allowed for these needs to be explored beyond the common and consistent 'balloon' whisk forms. In the attempt of gaining strength in individual loops, multiple strands were built up. The number of repeated strands, the tolerances between each, and the desired forms provided fiddly to deposit successfully. The largely open structure made any discrepancy more explicit. There was a greater differentiation between needed structural density of the handle and mesh frame. Various iterations of how to provide the handle with structure were explored.

APPLICATION EXPERIMENT 1 ; FINAL PRINTS

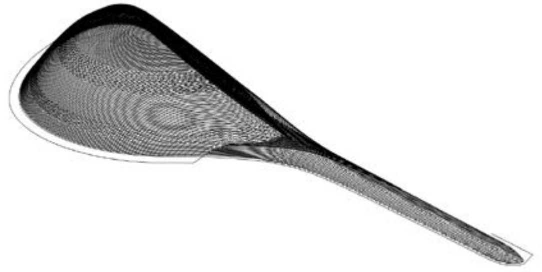
Below: Figure 86. (a-c) Author, AE1 Final Toolpaths

Figure 86(a)
Seive Final Toopath



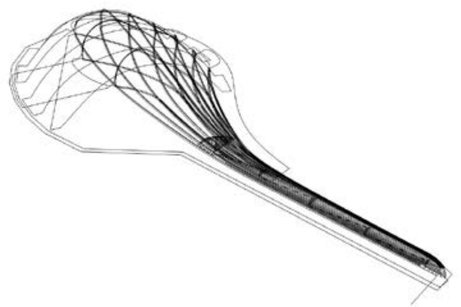
Print Time: 2:41:10
Material Used: 7870mm Coloured White ABS
Nozzle: N4
Settings: N4 and Custom Settings

Figure 86(b)
Measuring Spoon Final Toopath



Print Time: 05:24:10
Material Used: 9152mm Coloured White ABS
Nozzle: N4
Settings: N4 and Custom Settings

Figure 86(c)
Whisk Final Toopath



Print Time: 57:21:00
Material Used: 2846mm Coloured White ABS
Nozzle: N4
Settings: N4 and Custom Settings

The three piece kitchen utensil set nested together

Figure 87. Author, AE1 Final Set

Unique deposition approaches per piece

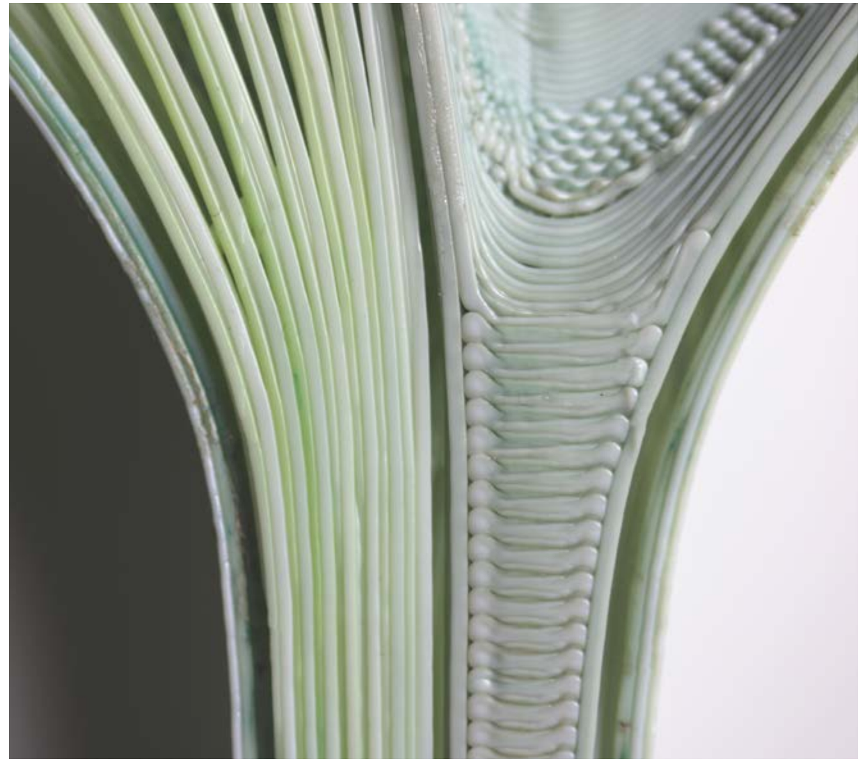


Figure 88. Author, AE1 Final Set

Directional, structural and tectonic diversity

Dense layers and open mesh deposition

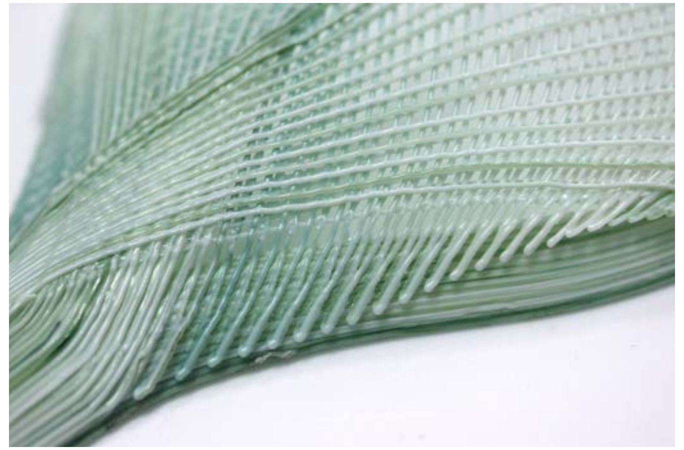


Figure 89. Author, AE1Seive

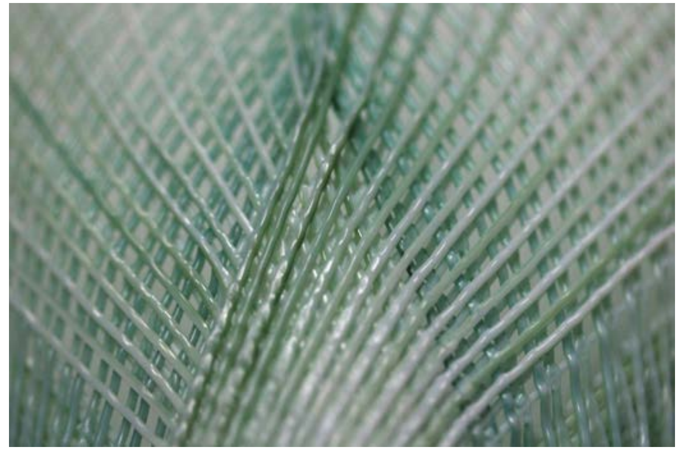


Figure 90. Author, AE1 Sieve

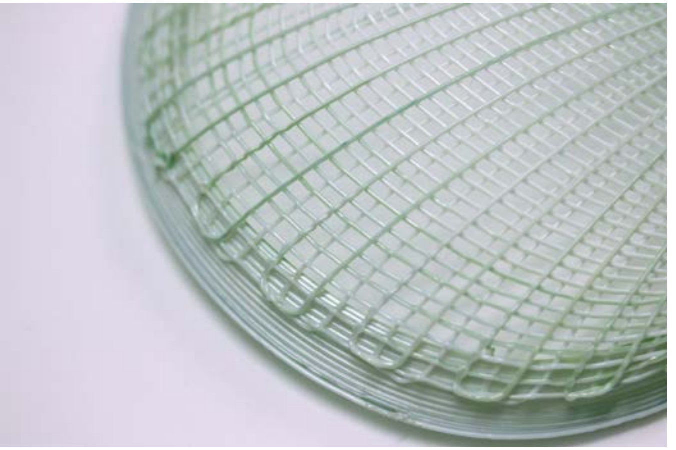


Figure 91. Author, AE1 Seive

Figure 92. Author, AE1Seive

Functional fulfilment - sieving flour

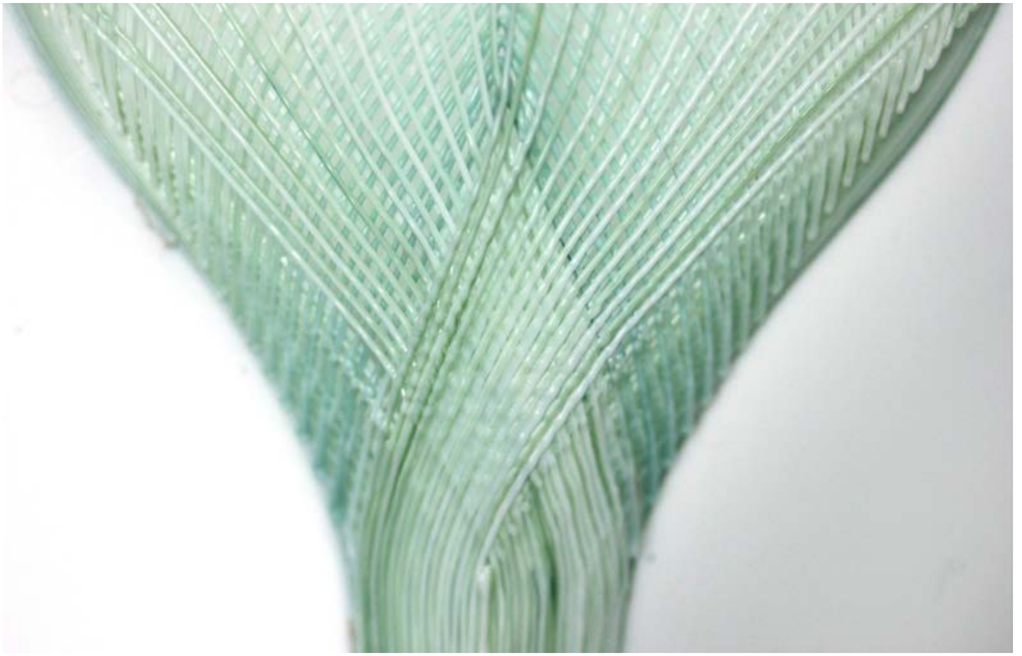


Figure 93. Author, AE1Seive

Figure 94. Author, AE1Seive

Using the form responsive method, material is seamlessly transitioned from a dense, solid handle, to an open weave spatial sieve top.

Figure 95. Author, AE1Measuring Spoon

With the measuring spoons requisites of water tightness and marking volume, a layer based approach was adopted. Through Designed Deposition, three-dimensional layering created a watertight structure, and change in patterning was used as volumetric markers.

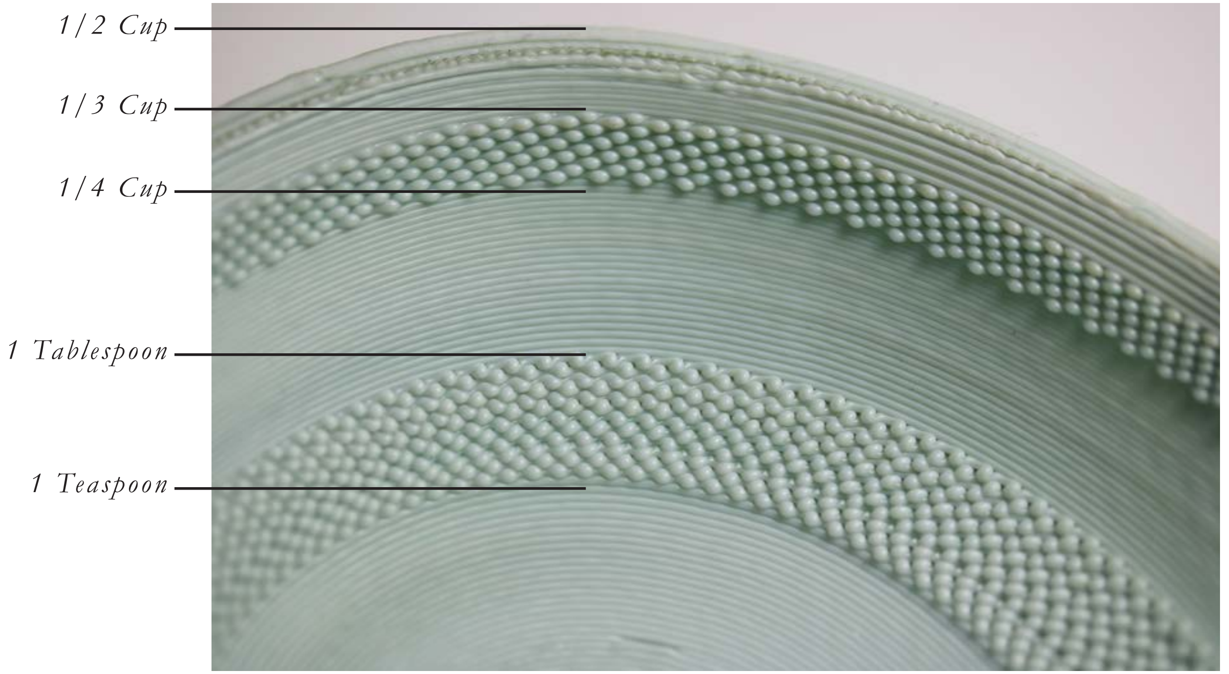


Figure 96. Author, AE1Seive

Patterning and tectonics within the measuring spoon - Some designed, others serendipitous

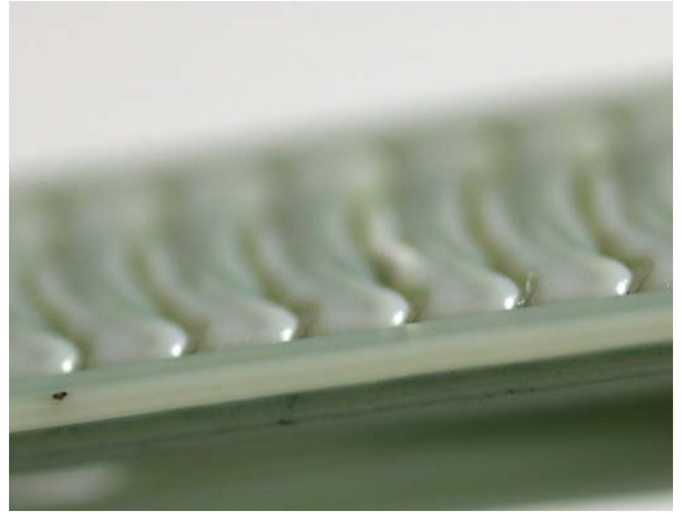


Figure 97. Author, AE1Seive

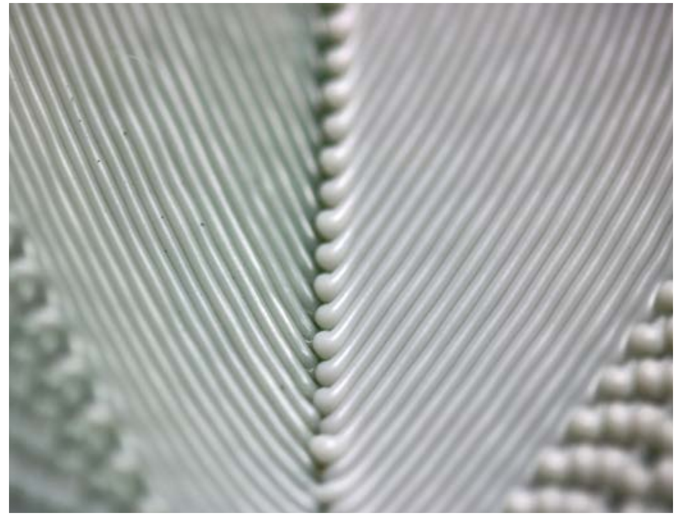


Figure 98. Author, AE1Seive

Figure 99. Author, AE1Seive

Figure 100. Author, AE1Seive

Once measured, substances can be poured smoothly from the spoon

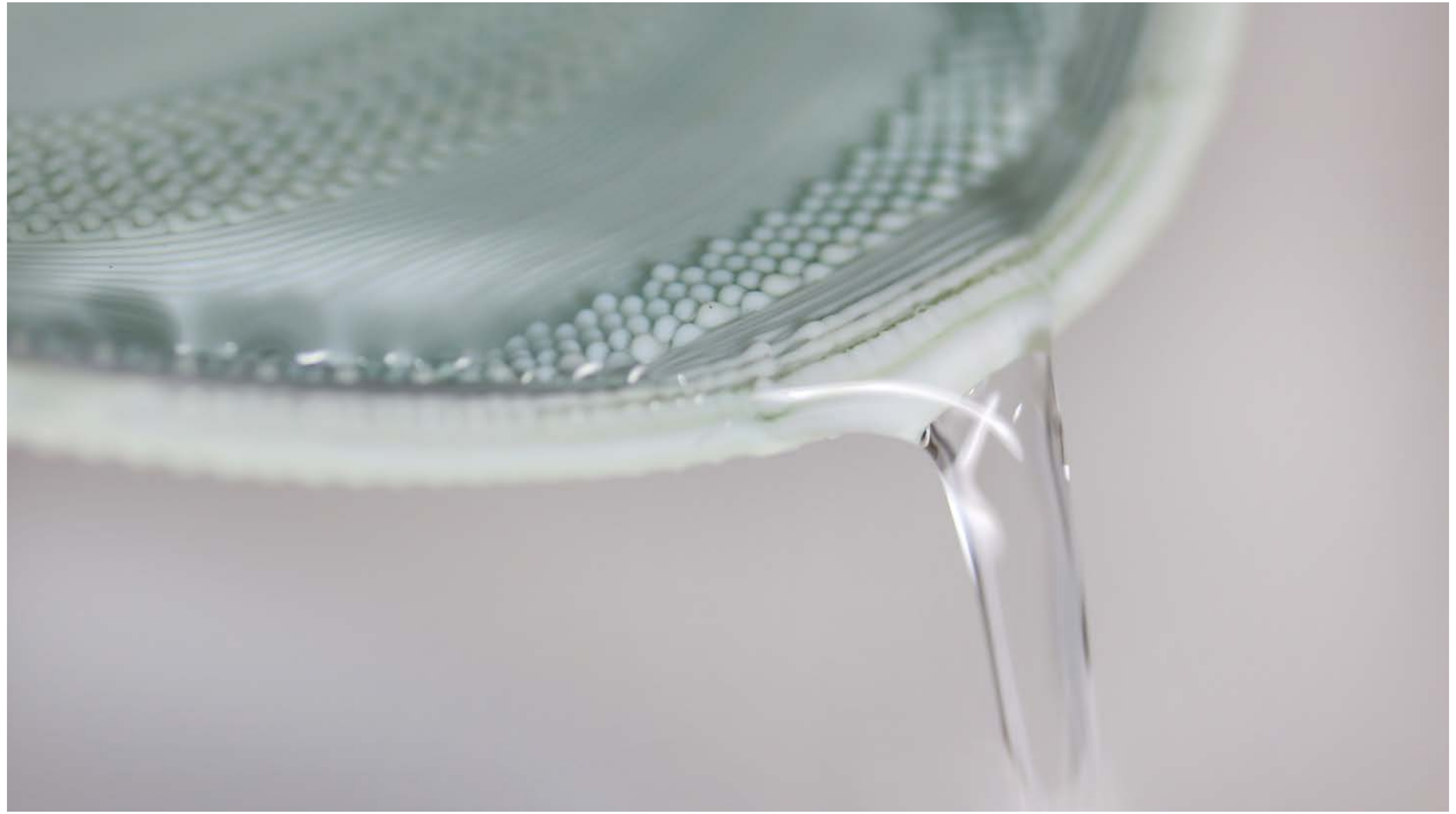


Figure 101. Author, AE1Seive

The whisk uses spatial curves that built up in density to construct an open, flexible, but fairly strong structure

Figure 102. Author, AE1 Whisk

Opposing directions of material strands improve structural integrity

Figure 103. Author, AE1 Whisk

Denser structure to gain strength in handle

Figure 104. Author, AE1 Whisk

Largely open forms

Figure 105. Author, AE1 Whisk

Figure 106. Author, AE2 Printed Iteration

APPLICATION EXPERIMENT 2 (AE2)

Mechanical Use, Structural Diversity, and Ergonomic Customisation; Application Exemplar; Computer Mouse

How and where material is deposited has been found to impact the structural integrity of a printed artefact significantly. This series gives focus to the structural and mechanical use of material dispersion. This intent was touched on in the Abstract Experiment Series (2.2); Series 3 : Structures, patterns and tectonics (SPT), where simple implementations of how patterning and directional deposition can influence structure were explored. This series sought to expand upon this, integrating electronic components, and connections between printed parts. A computer mouse was chosen to explore these areas through. How componentry was housed, how separately printed pieces could lock and release, and how material directions can inform structure and physicality became of primary interest. Ergonomics and the user were also brought towards the forefront in this application. On a static level, the Designed Deposition initiative allows for exploration of how forms and structure may influence use and interaction. Furthermore, the integration of parametric modelling for the development of toolpath allowed for ergonomics to become responsive to the user and touch upon mass customisation pursuits.

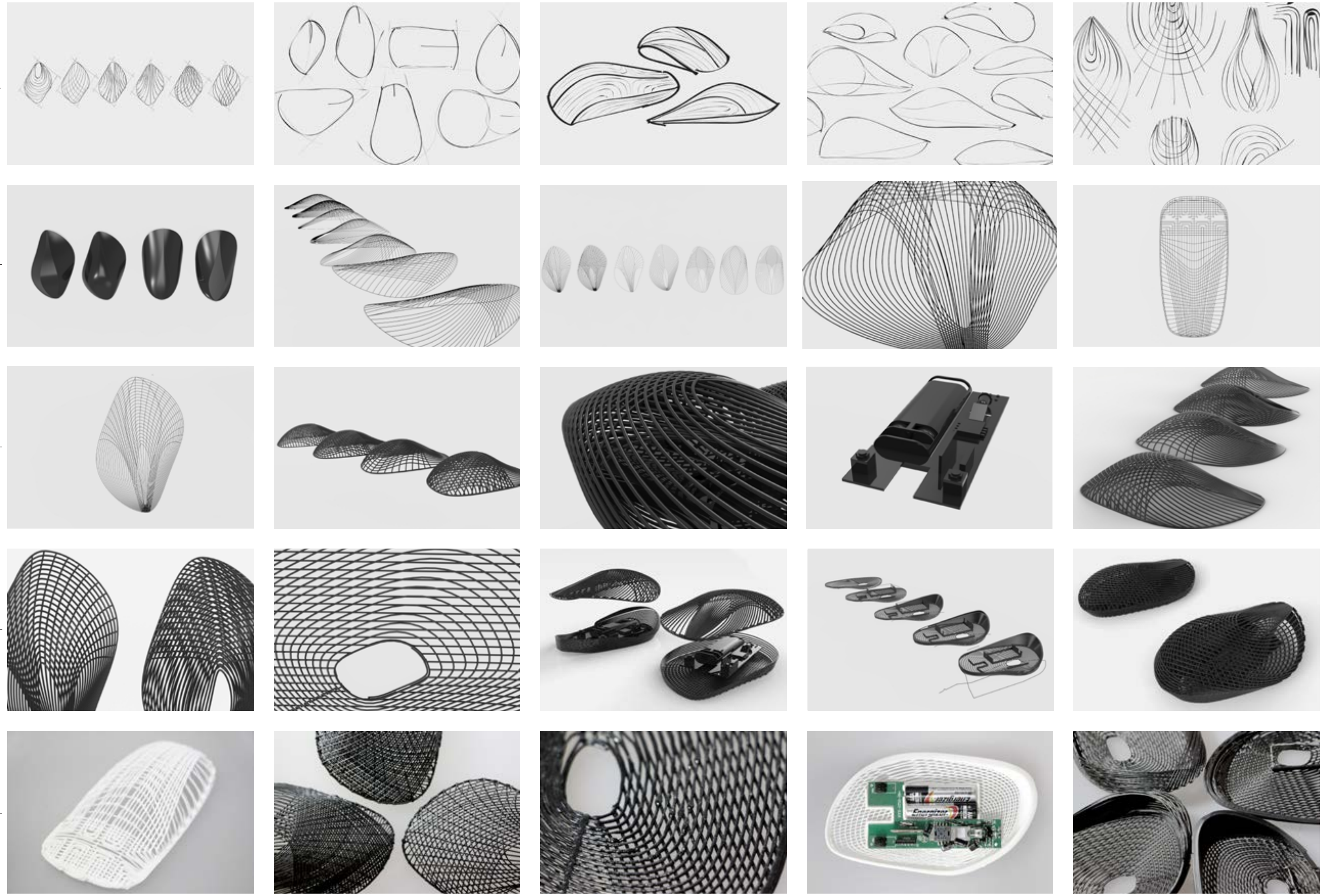


Figure 107. Author, AE2 Development Process

MOUSE DESIGN DEVELOPMENT

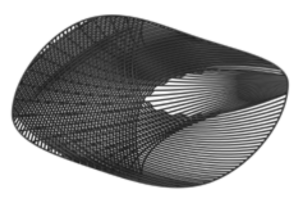


Figure 108. Author, Mouse Top Piece

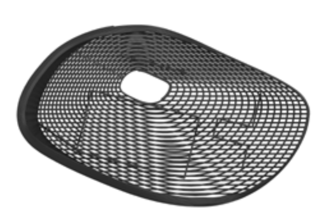


Figure 109. Author, AE2 Mouse Base Piece

The application of a mouse and its componentry provided defined structural and ergonomic restraints and requirements. Different types of mice were researched for their electronics and mechanics, in particular mice with touch sensors. The touch sense mice became of interest as they provided an opportunity for suggesting the touch interactions through material placement, directions and tactility. Early iterations based top material directionalities on the motions of a full touch sensitive mouse, in which different commands could be expressed through variations of swiping up and across with one, two, or three fingers. Subsequently, alternative touch mouse components were integrated. The chosen mouse had a touch sense pad for scrolling, but still used buttons for right and left clicks. These components allowed for exploration of both mechanical, and touch sense interactions. It was tested and proved that the sensor worked under a layer of printed plastic, and developed so that the sensor could be implemented directly during. Material directions were utilised for local structural benefit. Such as repeated parallel lines for areas of flex, and overlayed areas to gain strength. Housing for the batteries and electrical components were iterated upon, as well as the connections between the top and bottom casing pieces and how these could connect. The top piece was printed flat, but when attached to the base this piece it was held in a slightly bent state. This tension created was utilised to hold the two pieces together, as well as create more dynamic forms. A highly iterative approach was needed towards the final pieces to ensure a decent example of connection between these, as well as finding the right tolerances for holding the electrical components and still have useable buttons and general functionality. (Figure 110)

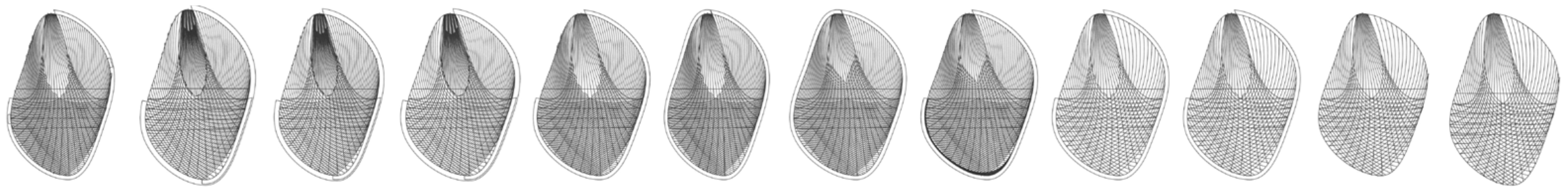


Figure 110. Author, AE2 Toolpath Iteration

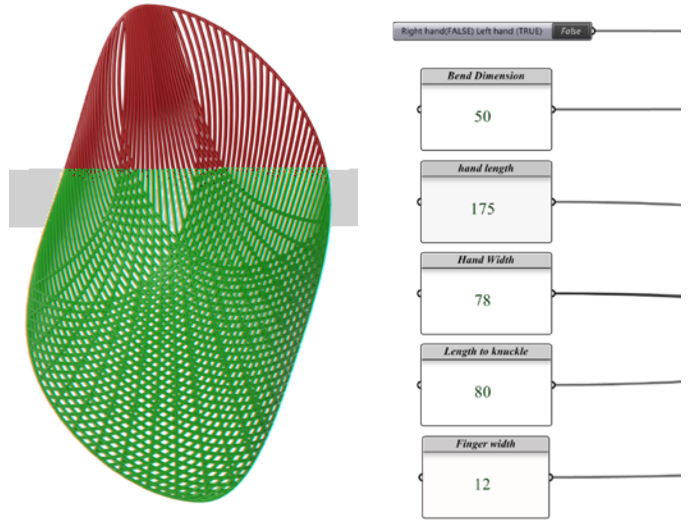


Figure 111. Author, AE2 Hand Dimensions 1

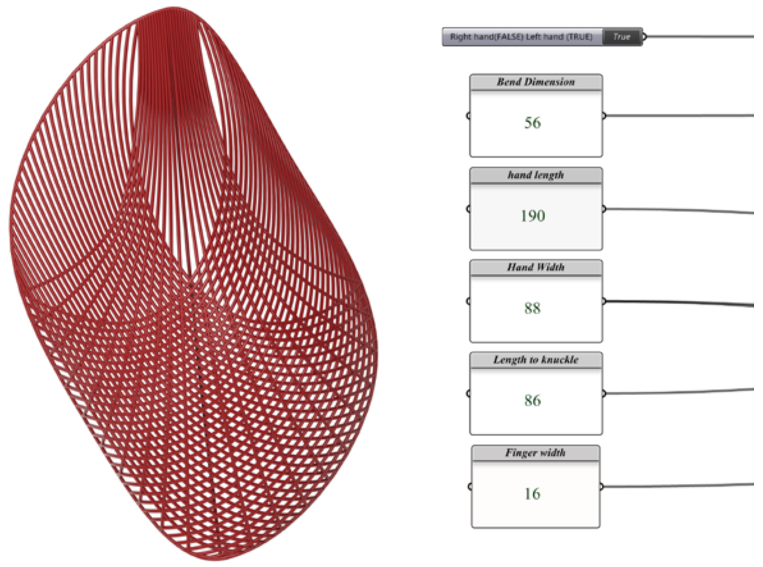


Figure 112. Author, AE2 Hand Dimensions 2

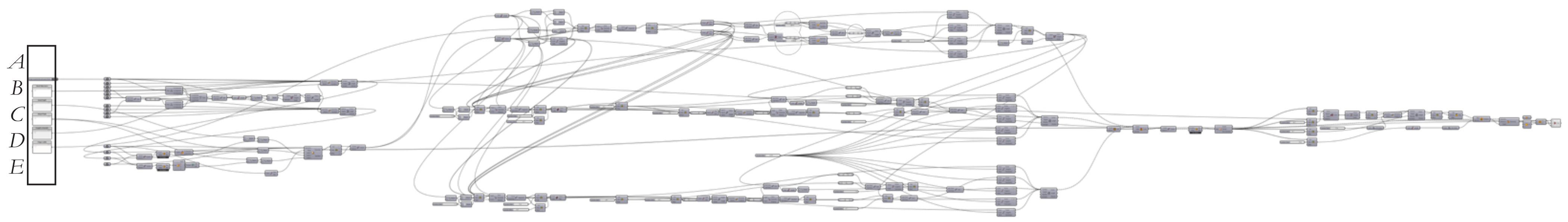


Figure 113. Author, AE2 Parametric Model

MOUSE - PARAMETRICS AND CUSTOMISATION

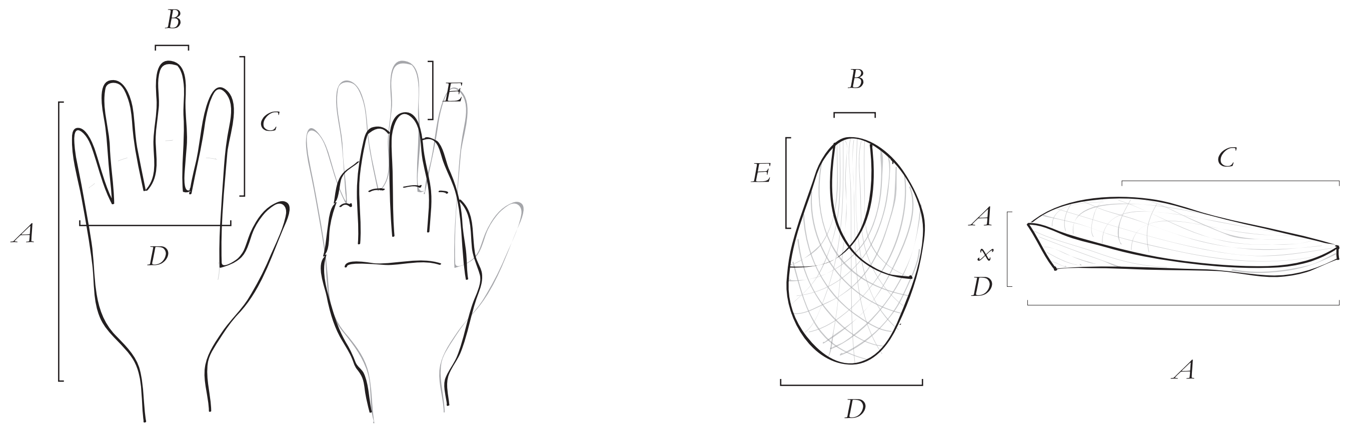


Figure 114. Author, AE2 Parametric Relationships Bewteen Hand and Mouse Dimensions

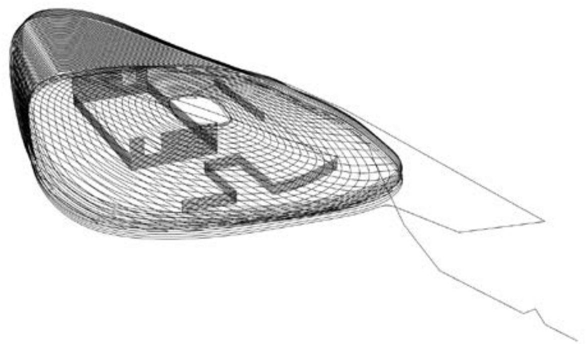
A parametric version of the mouse was developed to explore how the process could be developed for user customisable ergonomics. Relationships between input dimensions of a user hand and corresponding areas of the mouse were defined, as seen in Figure 114. For example, hand width and length helped to define the overall mouse size (A and B) and the distance between the fingers when flat and when naturally pulled back with corresponds to the length of the scroll section (E). The final printed mouse exemplar was created for the ergonomics of the author's hand. Figure 111 exemplifies a mouse created from these dimensions compared to the larger hypothetical hand seen in Figure 112.

Dimensions here were manually measured and put into the grasshopper script, but a more intuitive processes could be used to implement these values. Feetz (n.d.) is 3D Printing Shoe service which allows for customisation. They use an app to measure user dimensions digitally. A similar approach to digitally measuring the hand could be used to quickly and effectively gain multiple dimensions for ergonomic customisation.

APPLICATION EXPERIMENT 2; FINAL PRINTS

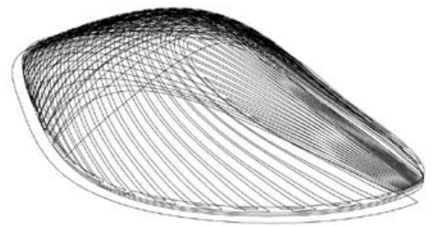
Below: Figure 115. (a-c) Author, AE2 Final Toolpaths

Figure 115(a)
Mouse Bottom Final Toopath



Print Time: 02:49:16
Material Used: 3713mm Black ABS
Nozzle: N4
Settings: N4 and Custom Settings

Figure 115(b)
Mouse Top Final Toopath



Print Time: 2:21:52
Material Used: 2541mm Black ABS
Nozzle: N4
Settings: N4 Settings

The two part mouse, housing internal electronics.
Designed to easily snap together and release from one-another.

Figure 116. Author, AE2 Mouse Assembly

Tab details for holding electronic componentry

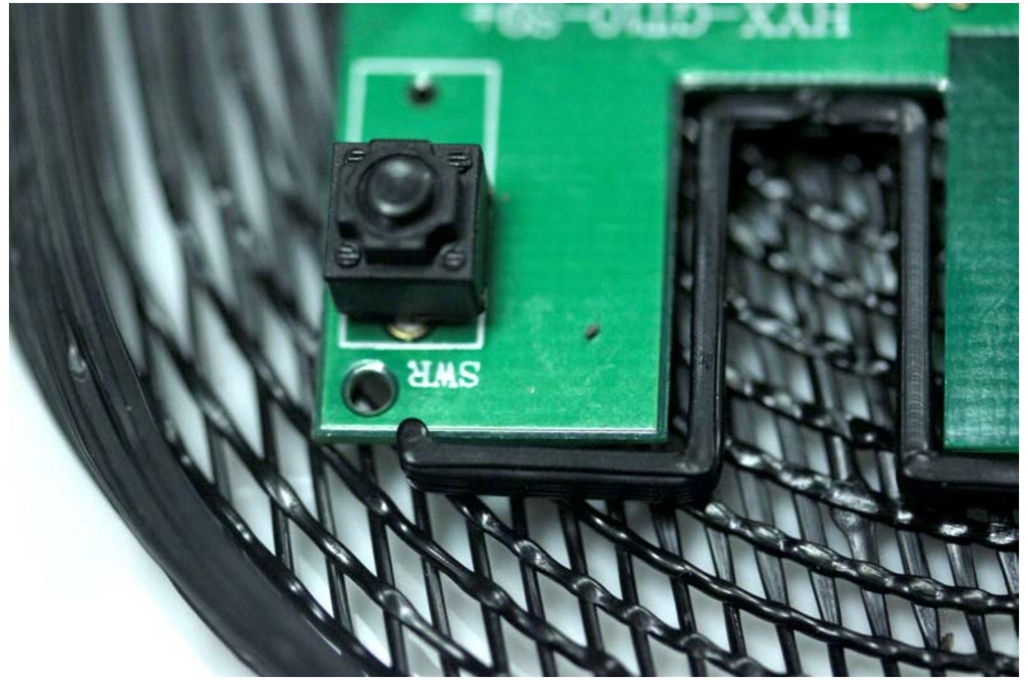


Figure 117. Author, AE2 Mouse Base

Base form is fitted to hold the top piece in bend position.

Figure 118. Author, AE2 Mouse Base

Structural variability
- Material flowing in aligning directions allow for flex and movement over buttons
- Overlayed structures used to gain strength for hand support
-3D layers for connection to snap together the two pieces

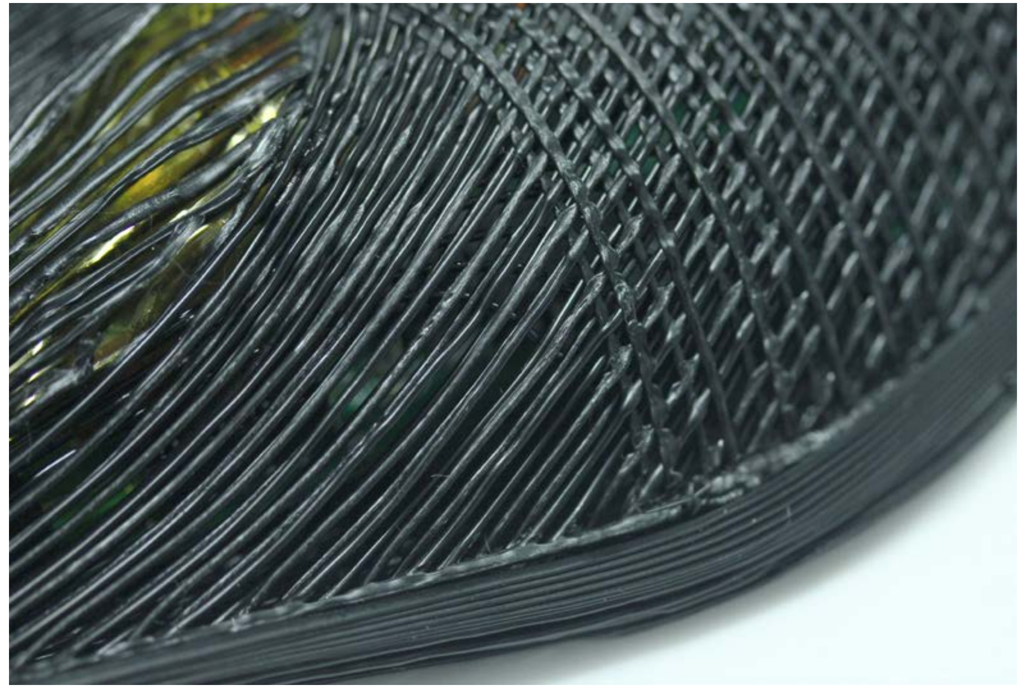
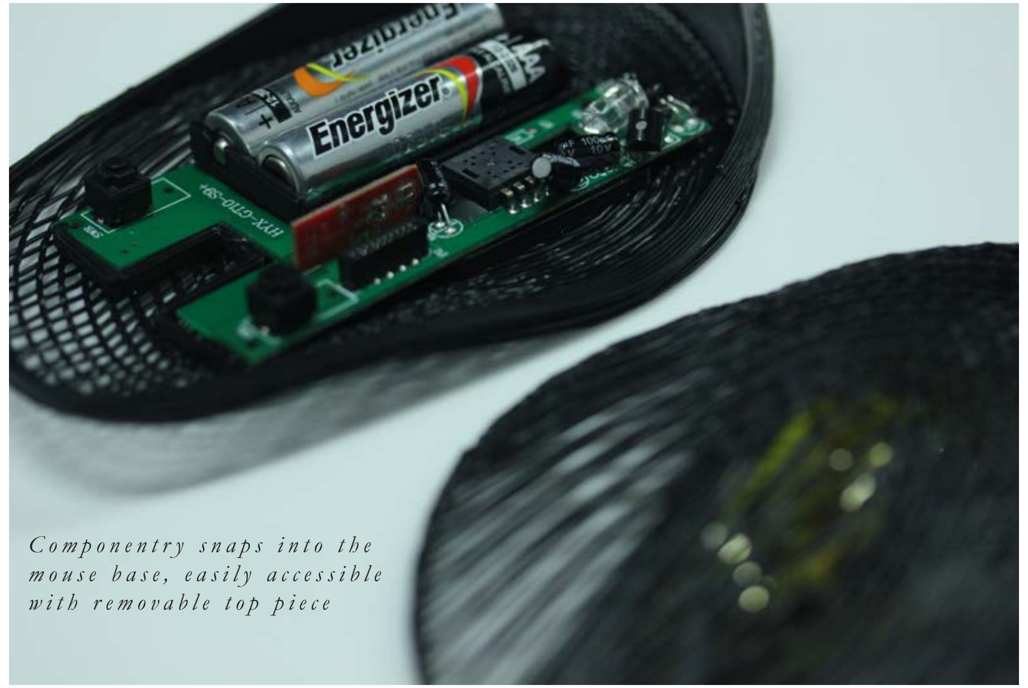


Figure 119. Author, AE2 Mouse Assembly



Componentry snaps into the mouse base, easily accessible with removable top piece

Figure 120. Author, AE2 Mouse Base and Top

Figure 121. Author, AE3 Printed Iteration

APPLICATION EXPERIMENT 3A, 3B &3C (AE3)

Parametric Patterning, Variable density, and Mass Customsation; Application Exemplar; Scale Furniture

Throughout the research, one particular approach towards Designed Deposition was exposed to be of intense value, repetition and patterning. To gain these patterns when 3D modelling within Rhino, a small inventory of commands were repeatedly used. Tween, Array, Project, Curve Divide and Interpolate points became habitual tools. The capacity of these commands magnify when being used parametrically. With the use of Grasshopper as the generative tool, there became opportunity for heightened intricacy of these patterning systems. This knowledge had already been utilised in previous explorations. Building upon the parametric patterns such as developed in the Abstract Experiment Series (2.2), Series 2 - Dynamic Layering, applicative value was pursued. A furniture context was defined to help discover implications of parametric patterning for aesthetics and variable density. The ability of generative modelling was utilised for further exploration of customisable and bespoke products. This developed to an exploration of how simple user interactions on defined parameters could bring large implications on the aesthetic, structural, and tectonic value of its artefact. There may be countless possibilities when it comes to patterning approaches. Here, three patterning systems were developed to build the furniture based experiments 3A, 3B and 3C, printed at a 1:6 scale.

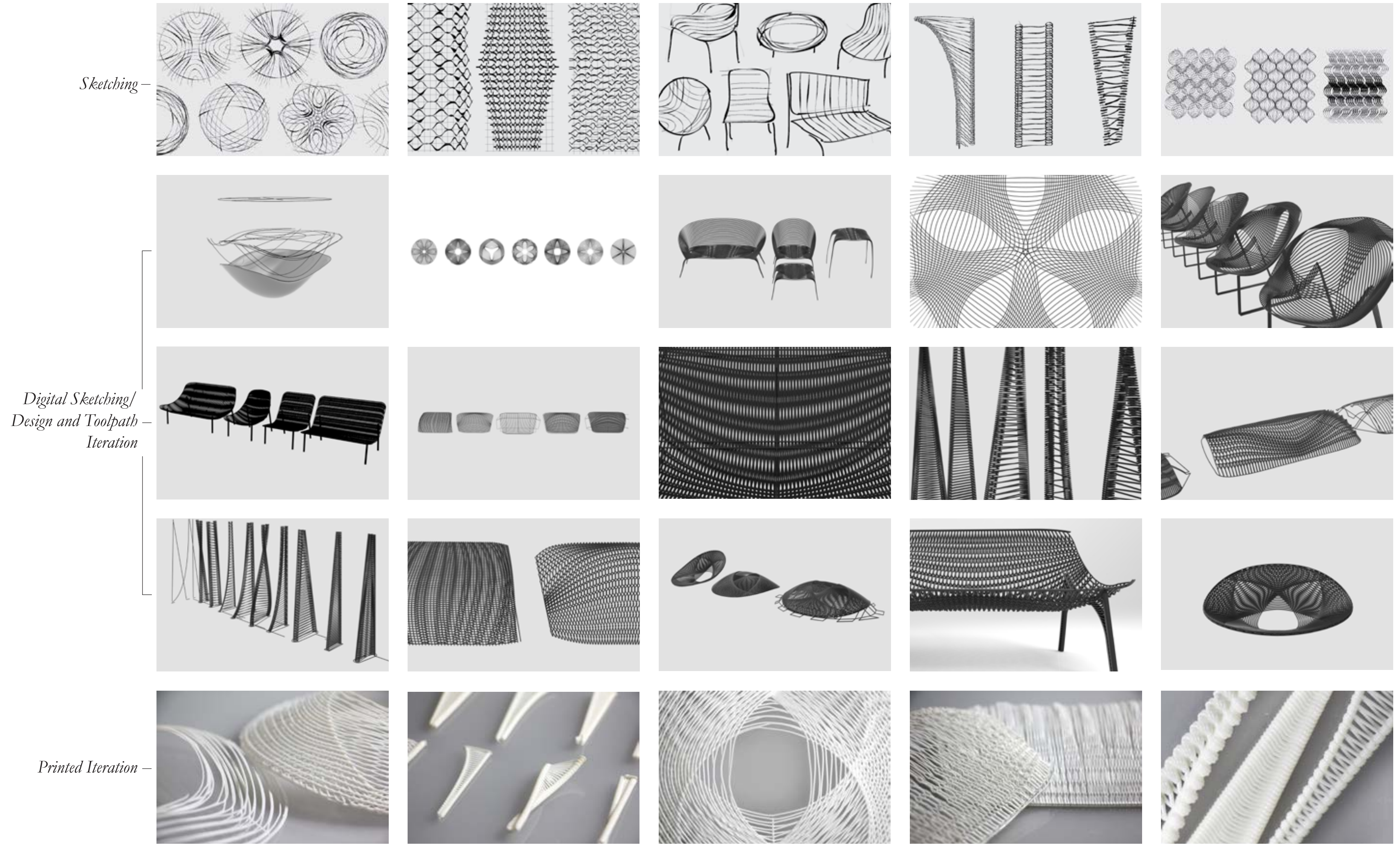


Figure 122. Author, AE3 Development Process

FURNITURE DESIGN DEVELOPMENT

The three-part study came to include two approaches to building primary furniture structures, and one for parametric legs to be integrated with both. It was pursued that these could all be controlled by limited, simple interactions, to create variable and unique outputs. Due to the parametric focus of this series, much of the design development happened within Grasshopper. Making the generative scripts more complex and user interactions simpler.

Below:Figure 123. (a-c) Author, AE3 Design Development

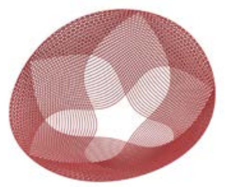


Figure 123(a)

Figure 123(b)

Figure 123(c)

3A - POLAR OVERLAY

The first parametric series began to build upon overlay qualities found in previous experimentation. Design development found interesting qualities when using multiple pattern or repetitious geometries conjunctively. A set of repetitious lines were first defined, becoming subsequently rotated around a central axis. In this series variety of structure became easily controlled. Deposition flowing in the same direction provided flexibility and overlaid materials more strength. The arrangement of overlaid vs flowed lines allowing for variable visual and physical effects.

3B - LINEAR (DIS)ARRAY

This patterning system was in seeking of new repetition based approaches that hadn't yet been explored. The creation of this patterning system became reflective of woven textiles. Linear patterns in two directions interact with each other create textural structures. This was produced from two sets of repetitious, uniform curves. One curve set was then used to split and rebuild the other, to create variability in structure. The series pursued to find implications for variable material qualities, through the convergence and divergence of lines.

3C - PARAMETRIC LEG STRUCTURES

A generative use of patterns was also used to create leg structures. These structures were to be used conjunctively with parts 3A and 3B of the application based experiments (3.2). For structural necessity, a partially layer based system was used to create compact form. They also utilised freeform techniques and patterning to allow the structures to reflect the qualities of the overall furniture piece. The script for the legs became integrated to the scripts of the main furniture structures, 3A and 3B. This meant that the legs could be placed and adjusted to respond to existing defined geometries, both functionally and visually.

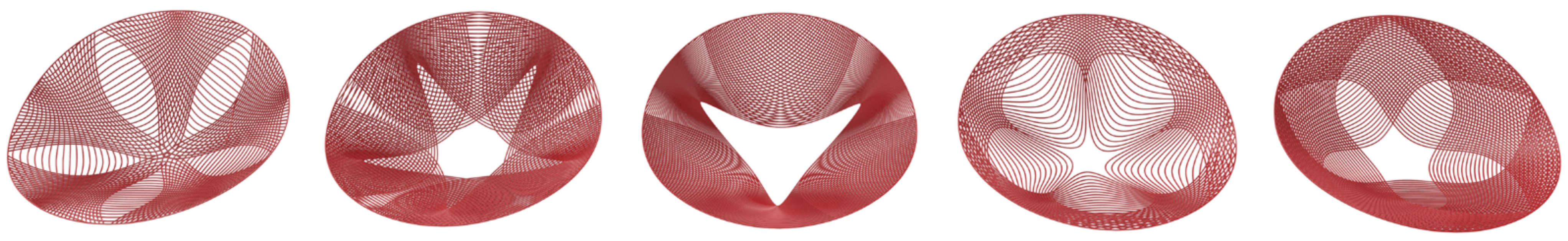


Figure 124. Author, AE3a Parametric Output Exemplar

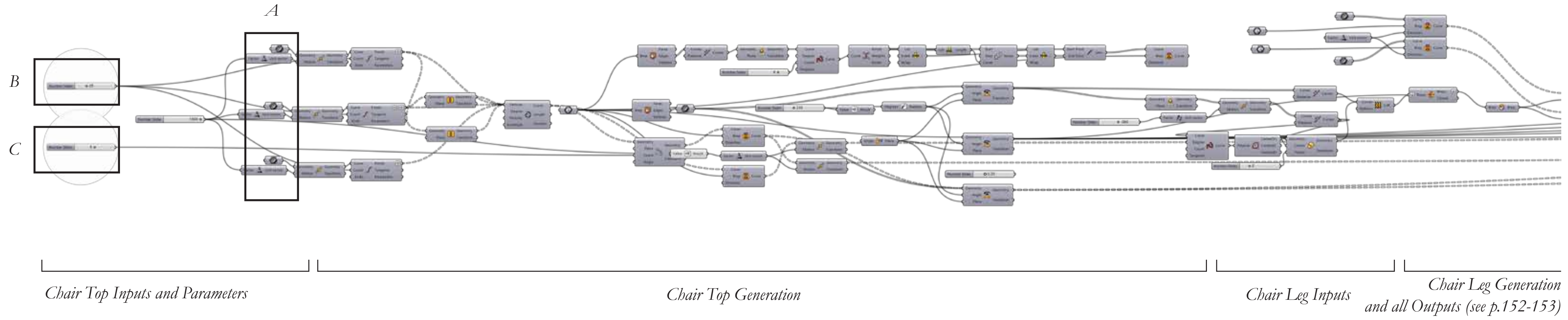


Figure 125. Author, AE3a Parametric Model

POLAR OVERLAY - PARAMETRICS AND CUSTOMISATION

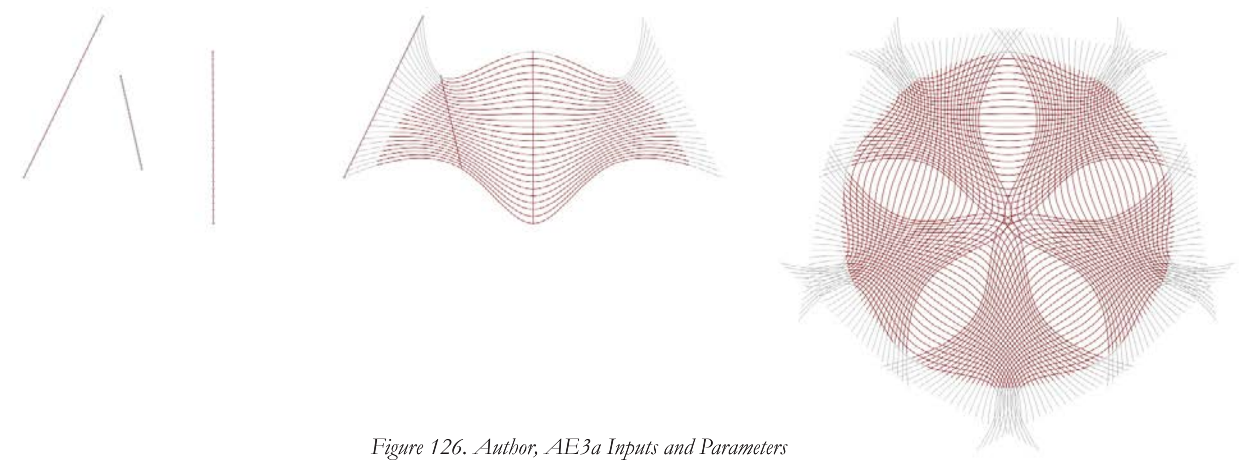


Figure 126. Author, AE3a Inputs and Parameters

INPUTS & PARAMETERS

A
Adjustable curves - defining geometries of the first pattern. The first two curves are reflected to make a symmetrical curve.

B
Divide curve count - Divides curves (A) into points, which are then interpolated into curves creating a set of repetitions lines such as above. These are subsequently projected onto a surface, cutting off any overhanging sections (Shown in grey).

C
Number of rotations in Polar Array of curves made in B

In this system, first defined are a set of curvilinear and repetitious lines. Then copied in a rotational motion, called a polar array. In the development of making these first repetitious curves simple to manipulate, they are defined by a small number of adjustable lines. These curves are divided by an adjustable number of points and new curves are created by interpolating these. The pattern is then polar arrayed around a central point through a user definable number. This process means that simple inputs and parameters can create a large range of patterned outputs with various implications on printed aesthetics and physicalities, here through just 3 inputs adjustments. This system does, however, limit the overall form to being primarily circular. To allow these abstract patterns to become three-dimensional, they are simply projected onto a chosen surface. The configuration of this surface and the integration of leg structures allow for adjustability of the output artefact. Here a circular based chair is explored, but tables or other pieces such as a table or stool could also be created through simply a revised surface for pattern projection and leg formation.

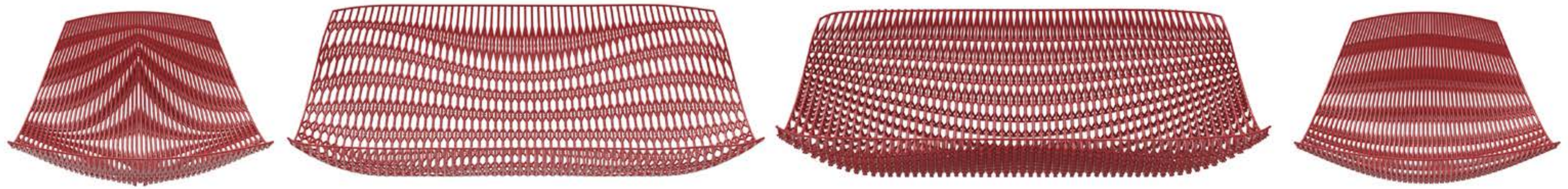


Figure 127. Author, AE3b Parametric Output Exemplars

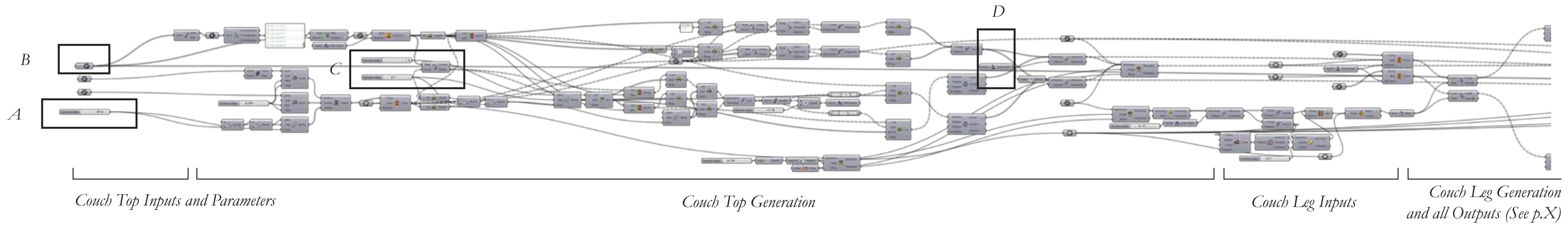


Figure 128. Author, AE3b Parametric Model

LINEAR (DIS)ARRAY - PARAMETRICS AND CUSTOMISATION

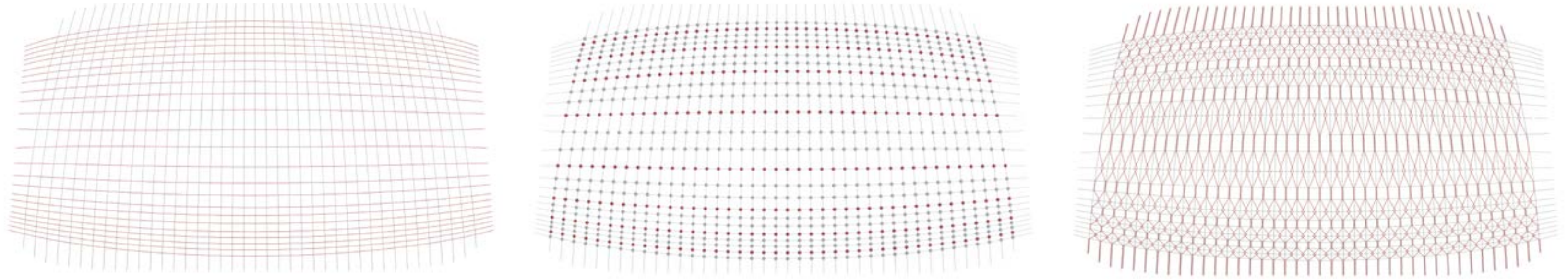


Figure 129. Author, AE3a Inputs and Parameters

INPUTS & PARAMETERS

A (Grey Lines)
Curve count - Defined the number of these base curves, increasing of decreasing material density.

B (Red lines)
Define/Adjust splitting curves - These curves control at what points the base curve (A) are split at, resulting in the formation of the pattern. The user can either adjust existing curves or create custom ones.

C
Curve Intersection - The intersection of these two curve sets (A and B) are the points at which Curves A are split. A pattern of points these points are then selected (here every third point, shown in red). These selected points are then moved away from their original position in multiple directions.

D
Motion Dimensions, how far the points move away from the original curve can be controlled. The intersecting points and the new, adjusted points are re-interpolated to create new, more intricate curves resulting in patterns such as above.

This Grasshopper script gained complexity in the interaction of lines and forms. Primarily defined by two sets of repetitious curves. The first set (A, shown in grey) of curves with adjustable density are projected onto the desired form to gain structural basis. A second fully adjustable input set of curves is defined (B, shown in red). This becomes the main controlling factor over material diversity and customisation. The intersecting points between the two sets are found, and a pattern in these is defined. Shown is the selection of every third point. The chosen points are then moved both towards an adjacent point, and away from the underlying surface form. A new curve is then defined with integration of the new, repositioned points, creating three-dimensional patterning. Resulted in a more informed, responsive and dynamic 3D relationship between the patterning and underlying form. The qualities found were slightly less ranging than that in the polar overlay system. However, this process was much more inclusive of forms, meaning allowance for more options of applications. Almost and surface could be integrated, thus a large range of furniture forms could be produced.

Figure 130. Author, AE3c Parametric Output Exemplars

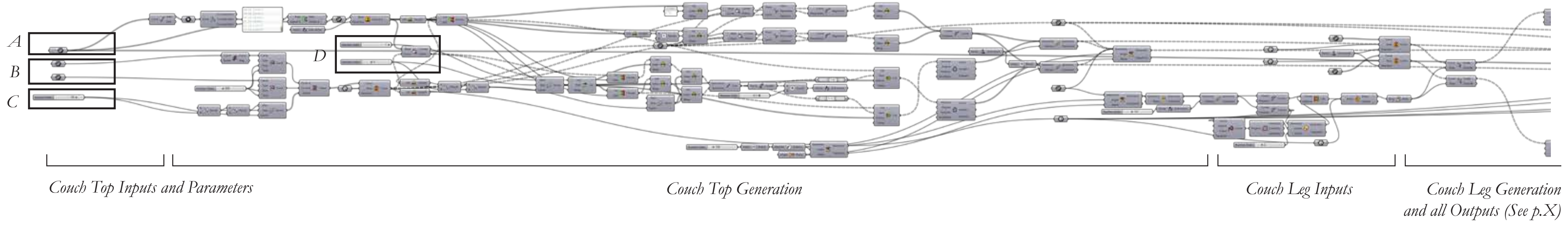


Figure 131. Author, AE3c Parametric Model

LEG STRUCTURES -PARAMETRICS AND CUSTOMISATION

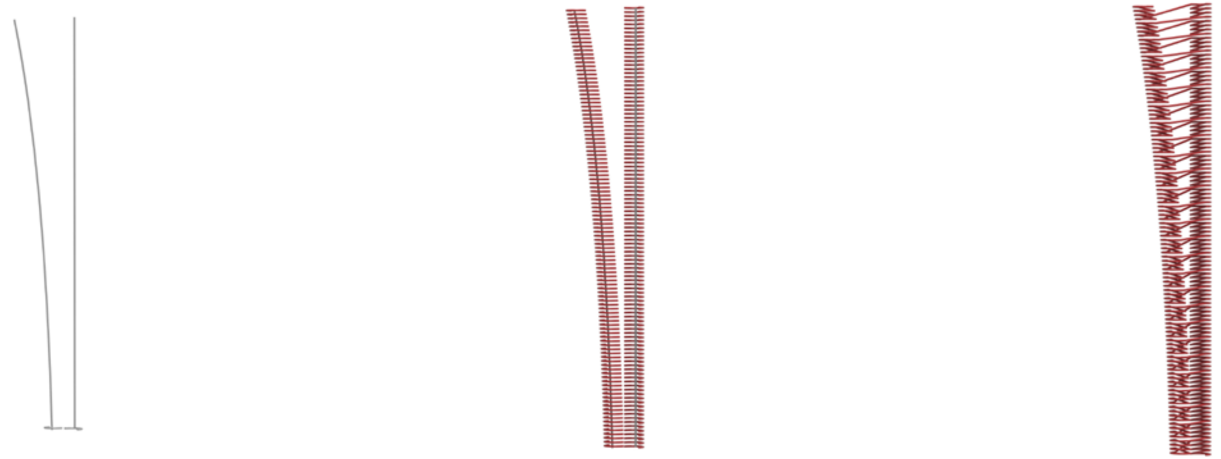


Figure 132. Author, AE3c Parameters ann Inputs

INPUTS & PARAMETERS

A (Grey Lines)
Custom form line - defining the overall shape of the leg structures.

B (Red lines)
Custom profile curve - the curve defining the profile to be layered up, creating the structure and geometry of the edges

C
Layer height - the main curves (A) are split at increments of an input height to define layer offset. The profile curve is then copied to each of these increments.

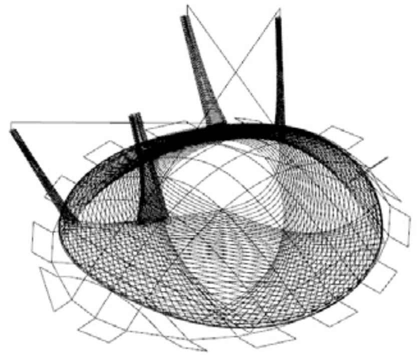
D
Toolpath Pattern- The two profile curve lists defined (C) are integrated into a pattern adjustable by the user. This pattern defines the path of curve interpolation.

A script for leg structure was developed continuing on the same parametric patterning and ease of adjustment incentives. This was designed to allow for responsive structures that could be adjusted to suit the intended output and functional requirements. The input geometries are two curves (A) which define the shape of the structure, and profile curves (B) which become the edge forms. These profile curves (B) are copied to points along curves A. At defined increments of the desired height between layers (C). This creates two lists of curves. These two lists are integrated together by an adjustable pattern. (D) The defined pattern controls the order in which the profile curve layers are printed. These curves are re-interpolated in the new order to create one seamless toolpath. The motions between the two sets create new structural strands, the frequency of the user defined pattern creating effect on density and structure. Integration between the parametric leg structures and the two furniture top scripts saw the development of the parametrics to become responsive to the functional needs of the desired furniture piece. For example, the form defining curves (A) of the leg structures were parametrically trimmed so that they didn't extend past the furniture tops, as well as so that the final piece would sit flat on a surface when upright.

APPLICATION EXPERIMENT 3A, 3B, & 3C; FINAL PRINTS

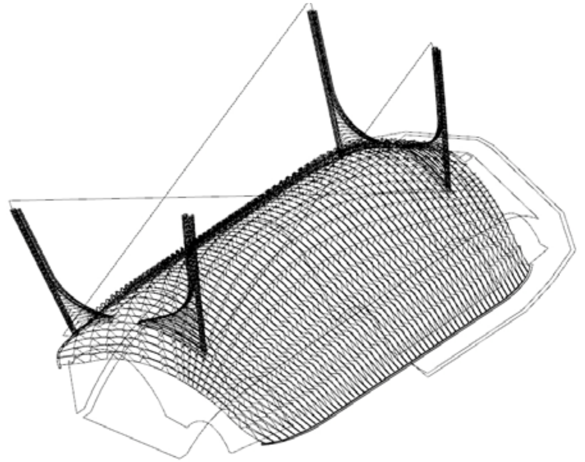
Below: Figure 133. (a-c) Author, AE2 Final Toolpaths

Figure 133(a)
Polar Overlay Chair Final Toopath



Print Time: 05:31:39
Material Used: 5867mm Coloured White ABS
Nozzle: N4
Settings: N4 and Custom Settings

Figure 133(b)
Linear (Dis)Array Couch Final Toopath



Print Time: 08:26:05
Material Used: 9168mm Coloured White ABS
Nozzle: N4
Settings: N4 and Custom Settings

The Polar Overlay chair being printed, with structural material and print motion strands to be removed after printing

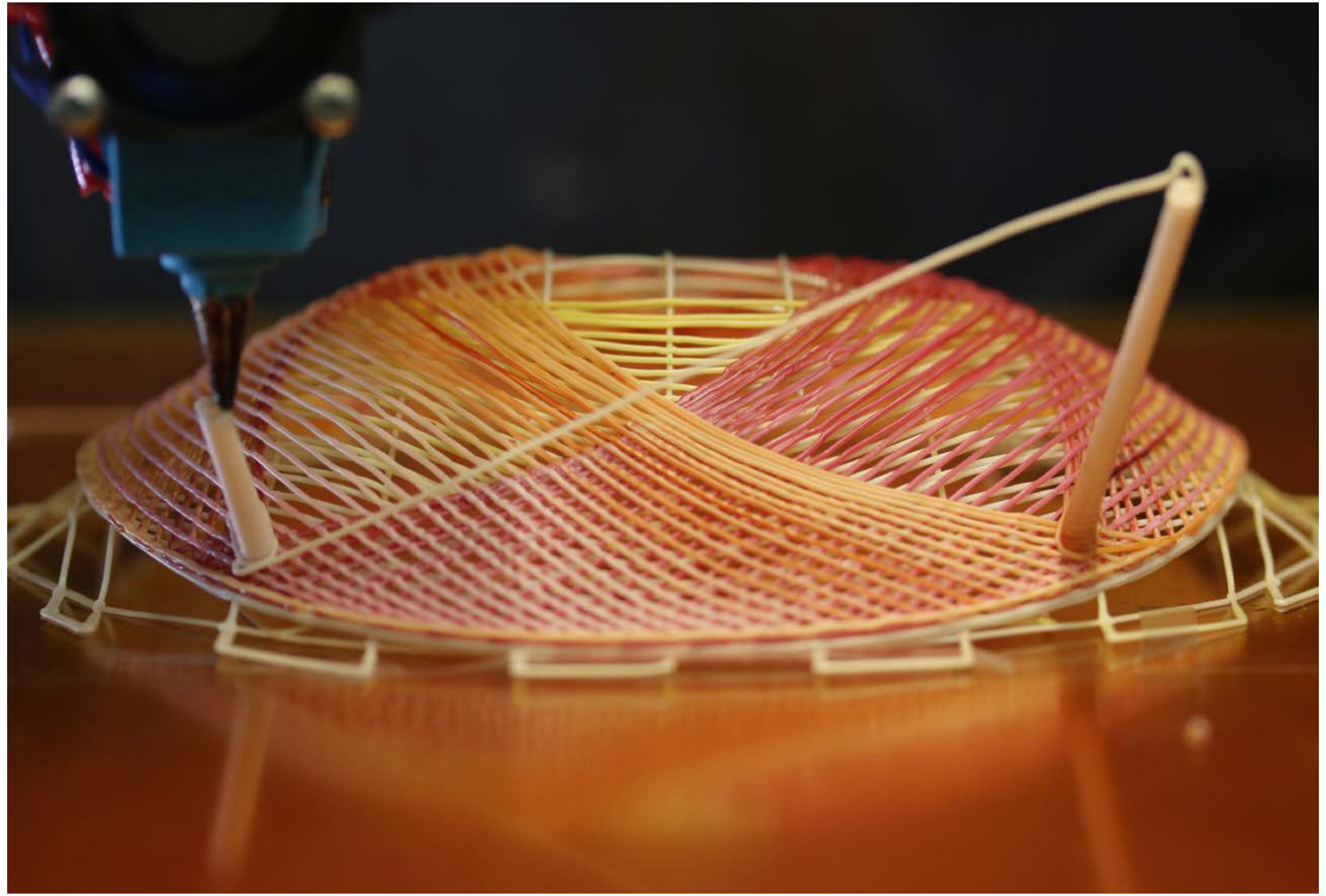


Figure 134. Author, AE3 Chair Printing

The formatting of material creates more structure around the seat edges and more flex in the centre

Figure 135. Author, AE3 Chair

Figure 136. Author, AE3 Chair

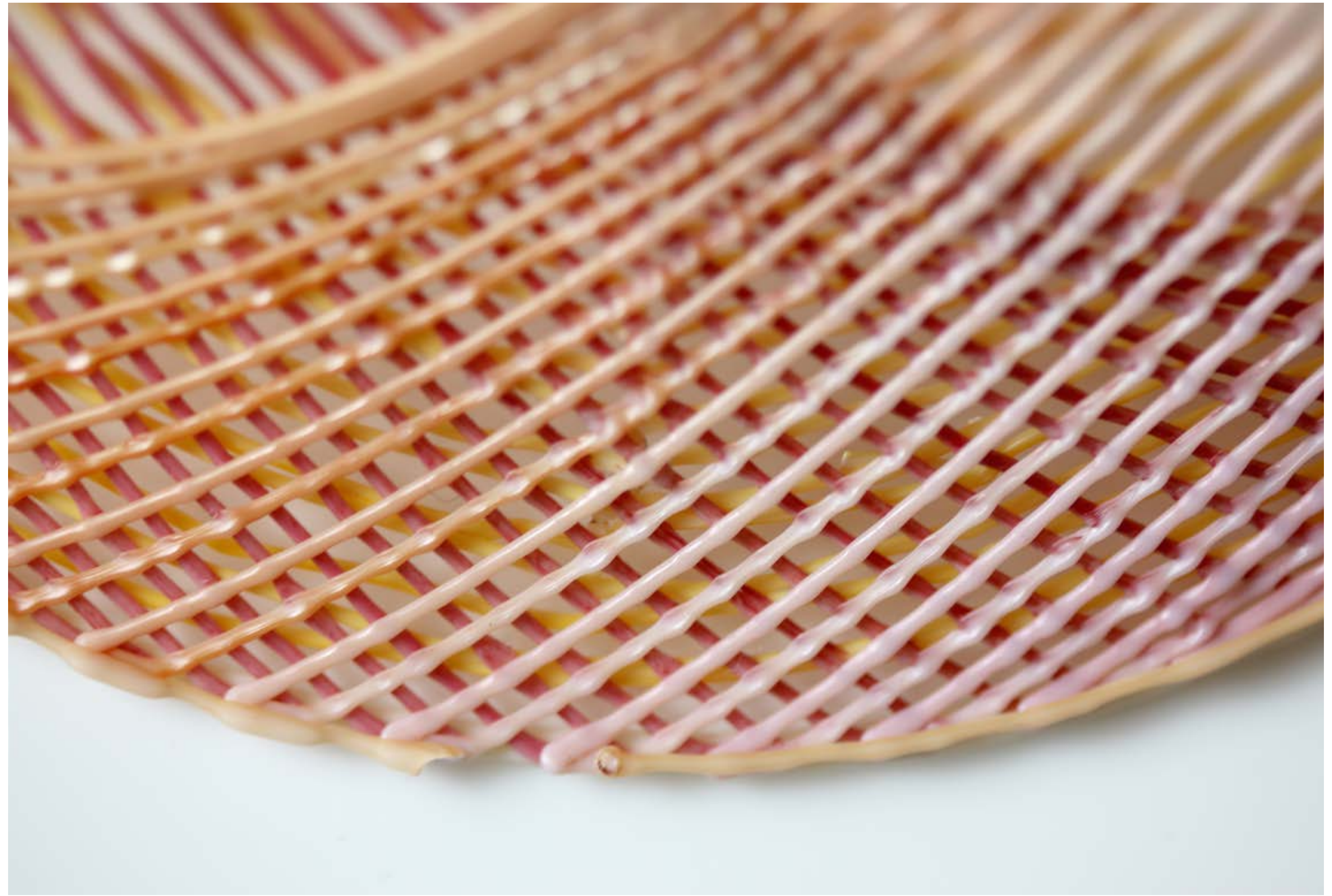


Figure 137. Author, AE3 Chair

Structural legs created through layer based, but three-dimensionally informed deposition, connecting to the underside of the chair base. The orientation or the legs flow along curves of the chair seat

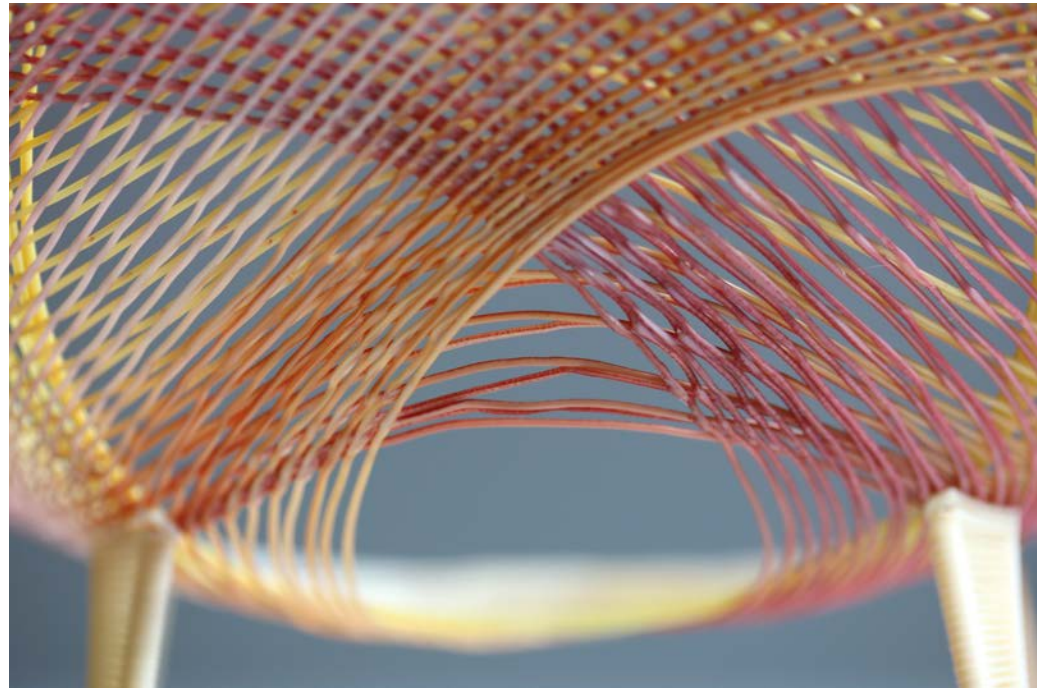


Figure 138. Author, AE3 Chair

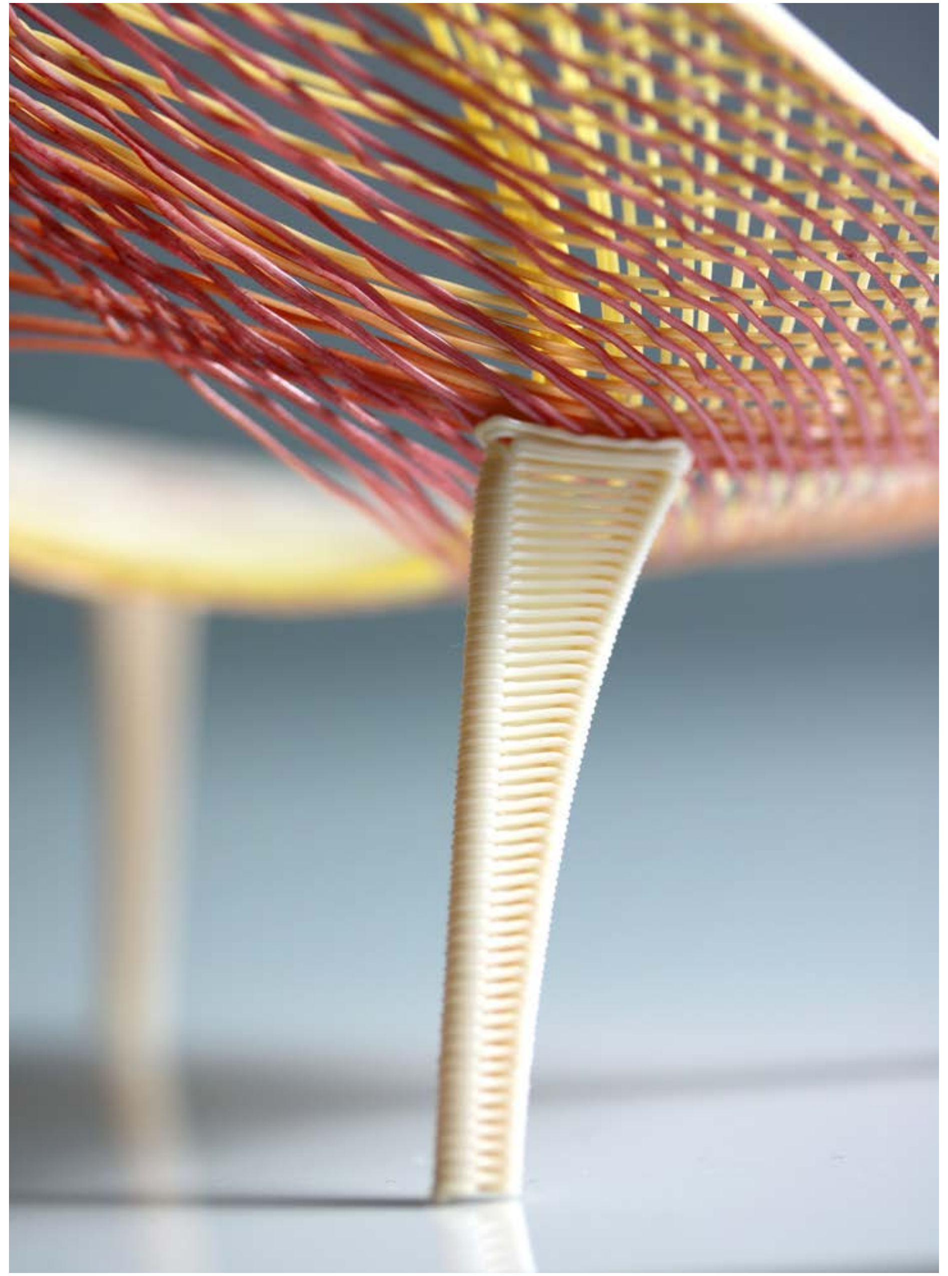


Figure 139. Author, AE3 Chair and Leg Structure

The Linear (dis)Array couch scale model, with structure based on the interaction of two linear patterns

Figure 140. Author, AE3 Couch

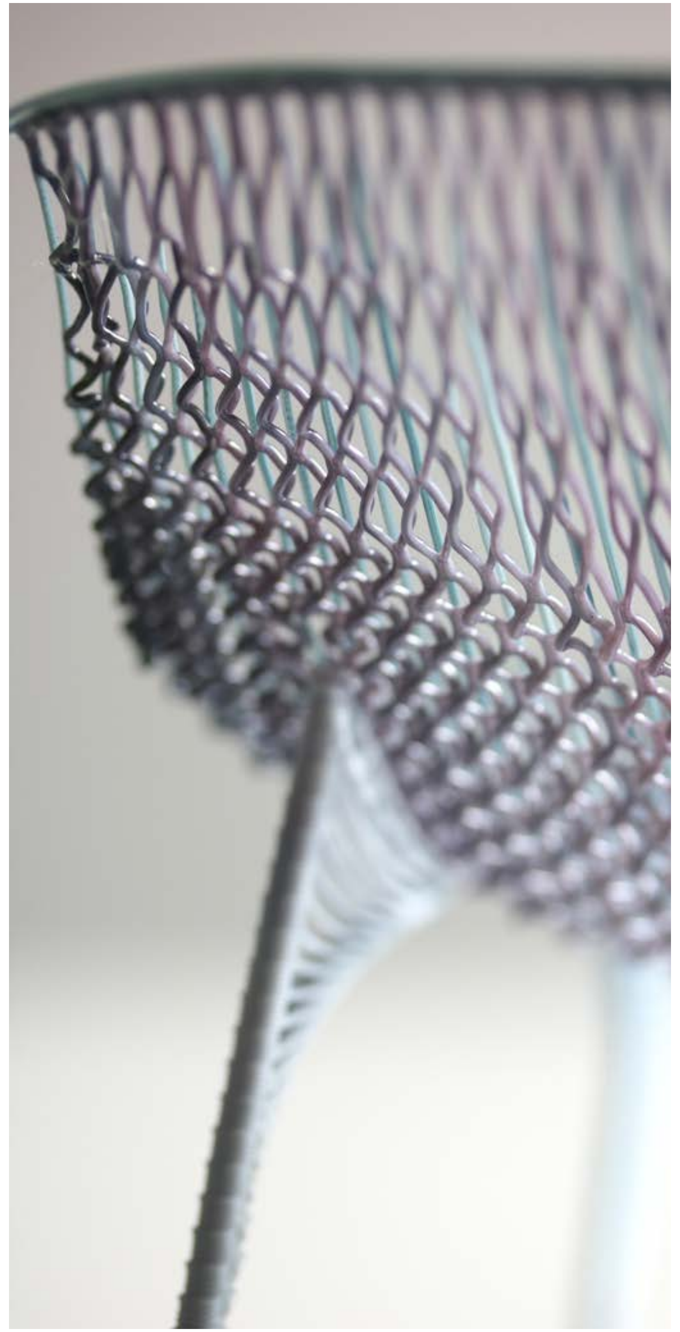


Figure 141. Author, AE3 Couch

Figure 142. Author, AE3 Couch

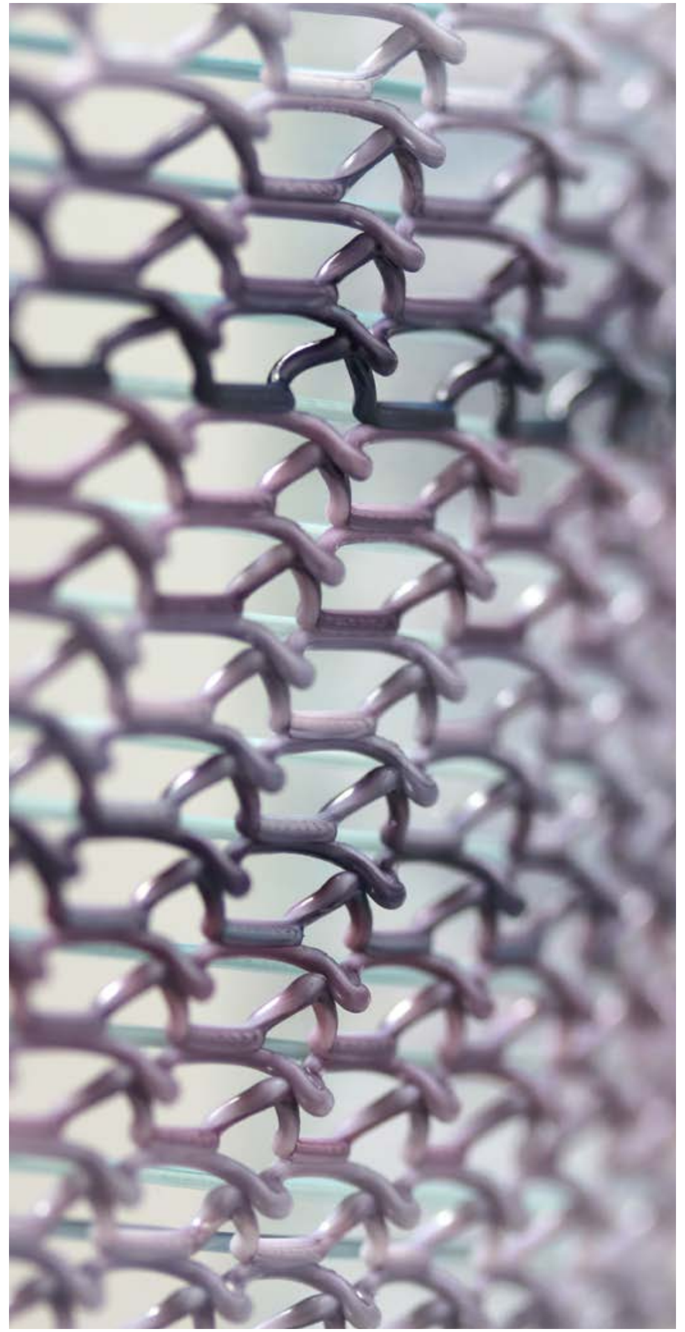


Figure 143. Author, AE3 Couch

Leg structure was designed to be more open in structure to reflect the visual qualities of the couch top

Figure 144. Author, AE3 Couch

DESIGN PHASE 2 CONCLUSION

The creation of the application based experiments was approached through unique perspectives for each artefact. Designed with synchronous consideration of material deposition and the intended output the series begun with unique starting points. Series 1 and 2 heavily responded to the brief and needs of its artefact for informed material deposition techniques. In opposition, Series 3 begun with abstracted material formations, to be designated the role of an object subsequently.

Through these object, electronic and furniture based pursuits it was understood how widely impactful material deposition is to the integrity of its printed artefact. Interesting visual, physical and tectonic qualities were found through various deposition design formations. Even so, many more opportunities lay dormant. A handful of techniques were explored comprehensively. Overlays of repetitious lines, three-dimensional layering, and other patterned techniques became revered, both individually and accumulatively. There are countless more opportunities for Designed Deposition. Due to the time-consuming nature of the custom processes further exposed opportunities were omitted. Developing artefacts with multiple surface areas and solid fill objects through designed deposition being of interest.

The step between delineating the general design of deposition, and executing the desired tectonics to a reasonable standard took a highly interactive process and a very intimate relationship with the manufacturing device. The development of a design became a negotiation of the desires of the designer and the limitations of the printer. A conversation of design iterations continued until the craftsman (the designer) the workman (the printer) and the material could agree upon a solution. Listening and watching the printer and material became a method of research in its own right. Sounds and signs expressed the comfort of the printer, becoming information towards future designs. This relationship and understanding allowed the authorship of the method of making to be reclaimed, and the printer to become a palpable tool for actualising digital craft. Computational systems and digital design tactics became of high regard. Diversity in digital techniques resulting in diversity in artefacts, both between prints, and locally within single designs. Direct and Parametric modelling techniques worked with lines, surfaces and forms to develop artefacts that embrace and respect its method of making and disregard any predetermined assumptions about how it should be constructed.

> *The digitisation of fabrication. And by that, I don't mean computers controlling tools. I mean computers that are tools. Computers that compute to build assembling digitally structured materials. We are at the edge of this digital revolution in fabrication. (Gershenfeld, 2006, 6:07)*

Industrial Design

Artefacts were developed through an Industrial design perspective. They sought notion towards, but not the development of, final design products. Materials, durability and consistency became clear factors inhibiting further the success towards end product quality. However, in embracing the manufacturing tectonics there becomes exposition of new tools to enhance design quality in novel ways. Enhancement and intricacy of form, tactility, interaction, and aesthetic based qualities were engaged with throughout the explorations. The diminished need of support material heightens the potential economic value of material and time compared to other AM methods, and largely reduces post-print clean-up. The value of AM for one-off forms allows for customisation opportunities, affecting identity and ergonomic value. These factors exposed development of unique path for AM towards the design of products that embrace the manufacturing tectonics as valuable to its designed artefact.

User and Mass Customisation

Through generative design processes, product users can gain control over the quality of output. Here, user input was considered another influencing factor towards the design of material deposition with regards to its output and user from commencement. Simple user interactions, available through parametric modelling, were found to grant large adjustments for ergonomic, visual, and structural influence from its user. The use of customisation through digital mediums and AM has been discussed by Gershenfield (2006) to benefit multiple areas. Including for allowance of the embodiment of self, 'personal expression in technology that touches passion: (16:50), such as explored through the highly adjustable models of abstract based experiment 3.

PART 4

4.1 - COMPARISON OF MANUFACTURING METHODS

Below: Figure 145. (a-c) Author, Support Material of Designed Deposition vs Standard FDM Prints

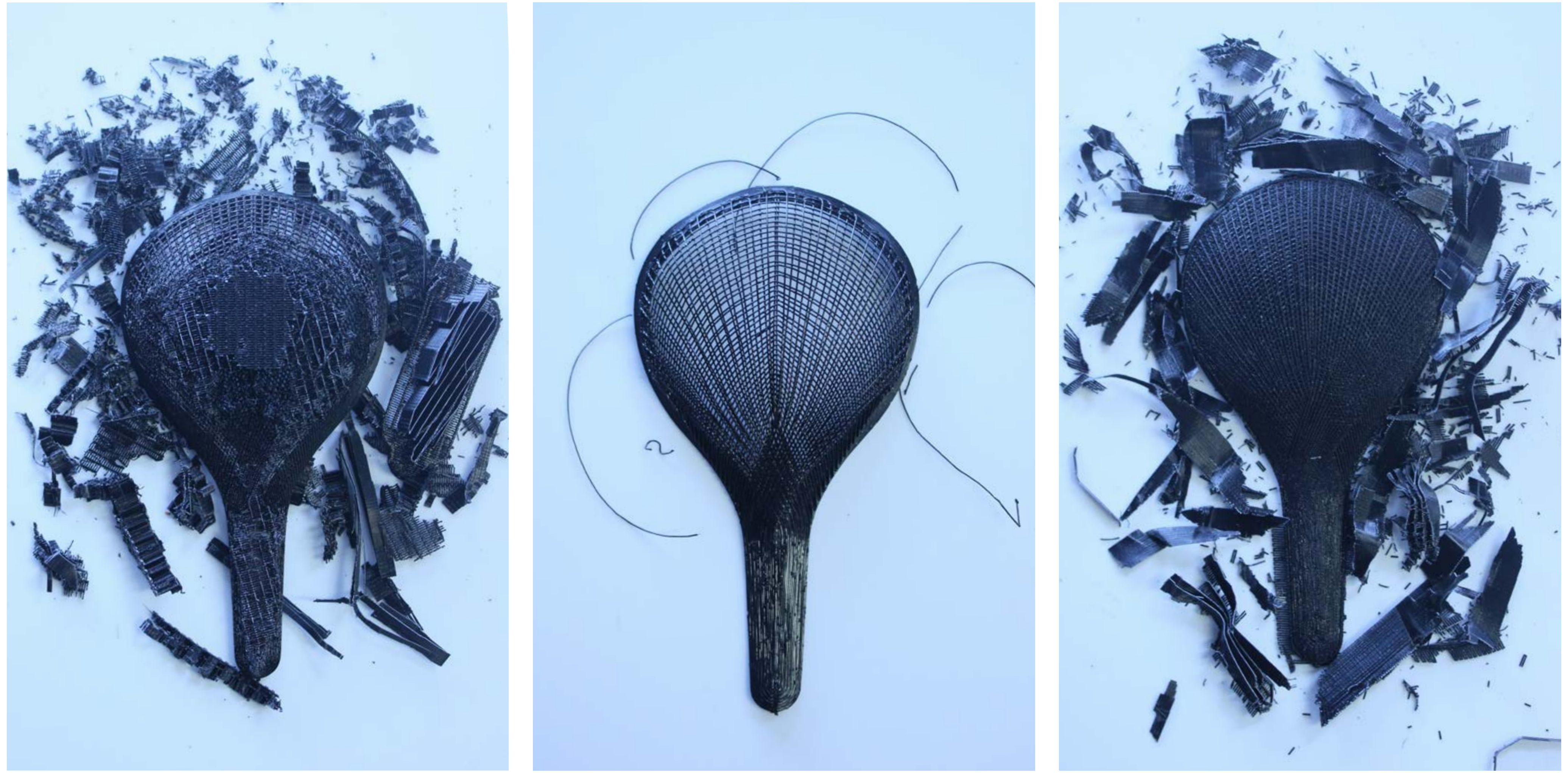


Figure 145(a)
FDM Print Oriented Facing Up

Print Time: 05:40:25
Material Use: 34522mm Black ABS

Figure 145 (b)
Designed Deposition Print

Print Time: 02:41:10
Material Use: 7870 Black ABS

Figure 145(c)
FDM Print Oriented Facing Down

Print Time: 04:40:56
Material Use: 25056mm Black ABS

DESIGNED DEPOSITION *compared to* STANDARD FDM PRINTING

Artefacts printed through the use of both Design Deposition and a standard FDM printing slicer were compared to further illustrate the differences between the systems. The sieve design from the application based experiments (3.2) was chosen as the form to compare, due to its variable densities, including both layered areas and open spatial methods. Two FDM prints were undergone, in both upward and downward facing orientations, using an UpBox and it's slicer set to the lowest support material settings.

Through this comparison, the disparity of support material reliance became explicit. As illustrated in Figure 145, the wastage of material becomes vastly reduced when using the Designed Deposition approach and utilising self-supporting build material, compared to the mass of excess material created from FDM prints using standard slicers. The removal of these support structures hindered the quality of the print, with many areas unable to be removed at all. The condition of the FDM prints were largely discrepant between the undersides which were effected by the contact of support structures, and the exposed upward faces which had areas of successful detailing. The print orientation of the Design Deposition print was considered during development in conjunction with material placement, resulting in a greater ability to print the open structure. The comparison highlighted the applicative value of both systems. FDM prints hold large value for prototyping, quickly moving a solid model from the digital to the physical to understand dimensions and forms. Designed Deposition is a much more intimate and labour intensive process to go from design ideation to printed artefact. However, once setup, both print time and material usage become much more economic, and material quality more appropriate to the final artefact.

Below: Figure 146. (a-c) Author, Designed Deposition vs Standard FDM Prints 2

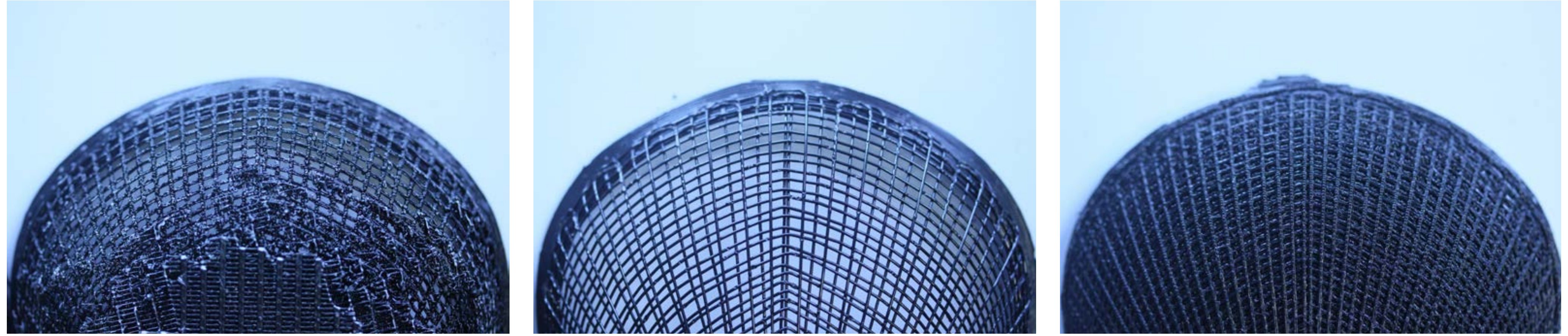


Figure 146(a)
FDM Print Oriented Facing Up Detail

Figure 146(b)
Designed Deposition Print Detail

Figure 146(c)
FDM Print Oriented Facing Down Detail

4.2 -DISCUSSION

OVERVIEW

Freeform 3D printing provided this research with opportunistic capacity for new approaches to building additive 3D forms. Common approaches to defining material deposition were disregarded, opening space for new techniques for building form. Self-supporting build material and fully simultaneous motions were tools utilised, revealing both promising opportunities and novel limitations for the creation of extrusion-based AM artefacts.

This research illustrates that a designer with the ability to learn the language of appropriate CAD and CAM technologies can become an informed mediator between the digital and the physical, directly defining three-dimensional built form through the design of repetitious curves. The designer can reclaim control of the manufacturing method from automated algorithms, making it an intrinsic part of crafting artefacts. Deposition is curated with consideration of aesthetic, functional and tectonic qualities in both form and materiality. Intended use and intended user interaction becoming integral with Designed Deposition and the material is crafted with consideration of these and various other aspects specific to it's artefact.

Some beneficial features of AM were, however, impacted by this new technique. Undercuts became increasingly difficult to execute when a strict ground-up basis was not utilised and the complexity of form was restricted. While form may become restrained in some circumstances, the qualities of materiality, aesthetics, structure and tactility gain the capability to become revitalised and diversified. This research illustrates 3D printing's capability for informed deposition, revealing potential for its application in the production of bespoke products, not only rapid prototypes. Designed Deposition allows artefacts to thrive through the method of their making. The process no longer seeks to produce any input form, instead only those which respect and embrace both the opportunities and limitations of their manufacturing method.

A research through design methodology was adopted for the exploration of possible techniques and applications of Designed Deposition. The Abstract Design Experiments (2.2) began to discover possible print tactics of significance, as well as identify areas of restraint. Each series had a unique focus, and each experiment, be it 'successful' or not, presenting constructive information. These experiments began to explore possible new computational systems, utilising both direct and parametric modelling techniques. Designs were created with lessened regard to its output. Instead, there is focus on both visceral and technical value gained from its Designed Deposition.

The findings of the Abstract Design Experiments (2.2) informed the subsequent Application-Based Experiments (3.2). These experiments were not intending to create final products, but pursued further knowledge on the process and its applicability through self-defined direction and context. Object, electronic and furniture based outputs were developed to show that various product and user-based requirements could be obtained through freeform 3D printing. Illustrated was just how influential material deposition was in the variation of both visual and physical factors. Values of density, tactility, materiality, ergonomics and structure were tailored to create one-off creations as well as those which were customisable on the mass scale. it was explored how parametric design could allow users to customise factors including aesthetic quality and structural variability. This integration of user input furthers the concurrent consideration of both the user and the output when designing an artefact and material deposition.

3 AXIS, 6 AXIS AND SCALE

Performed through standard 3-axis FDM printers, this research sought to discover the implications of the spatial printing method compared to its largely explored 6-axis counterpart.

The main impediment, as anticipated, was the lessened dexterity that allows for undercutting and the ability to manoeuvre around existing geometries with greater freedom. As aforementioned, this can limit geometry and complexity of an intended artefact. Through tactical strategies, some geometric restraints could be overcome. However, artefacts and forms were chosen with respect of the method of making, accepting this process for bespoke and specific creations that embrace both opportunities and limitations presented of the process.

The value in using this simpler technology lies in its exposition of the process to a more inclusive audience. A high level of specialised knowledge and equipment are required to integrate and control both a robotic arm and a custom extruder, compared to the already equipped FDM printer. The limited size and dexterity of a standard printer could be seen as impediments in some contexts, however as a cheaper, more accessible, and easier to control technology, these can also become main benefits.

When using FDM printers, new software becomes the greatest barrier to overcome in seeking engagement with freeform 3D printing. Software development and inclusion of both 3 and 6-axis technology could begin to democratise the adoption of this process, becoming inclusive audiences without specialist technology or knowledge.

> *The most significant boundary currently not only being crossed but being dismantled is the boundary between professional and amateur, or more pertinently, between 'designer' and 'user'. Recent design methodology has stressed the importance of taking a user-centred approach, but has not envisioned a position where designer and user are essentially one and the same. This change in perspective has the potential to transform design education, design practice and the consumption of design.*
> *(Atkinson, 2010, p.137)*

BROADER IMPLICATIONS

The implications of this technique extend further than that specifically found of this, or other individual research.

A major insinuation of the freeform process is the curated and vastly reduced use of material and energy. The immensely decreased and often non-existent requirement for support material allows for AM to become much more sustainable in the use of material. Informed material deposition and only placing material where necessary sees this further exhibited. The implementation of technologies such as finite element analysis (FEA) could see material efficiency developed further still.

For these same reasons, printer motions are also decreased. While this seems unimportant, the implication for future is largely reduced print times. Through this research, printer motions during three-dimensional movements were extremely slow to allow for material to cool and self-support. In other research, printer speed has been increased through technology development. This is most commonly achieved through integrated cooling systems, and also by creating steady temperatures and higher torque. (Curvoxels, 2014-2015). However, the foremost advance needed for significant progress is the development of materials specific to this process, with greater adeptness for spatial solidification.

Other advantages of AM in general are tool-less production, local printing, and lessened transport. Once setup, the necessities of AM requires no physical inventory apart from the input of material. Its digital nature now removes physical inventories of object specific tooling, and stock equipment such as moulds. While this has been the case since the advent of AM, spatial or custom extrusion methods could in future find benefits towards the merge in these technologies with larger scale production. Other benefits of the process are reduced post-print cleanup, labour, material and energy usage.

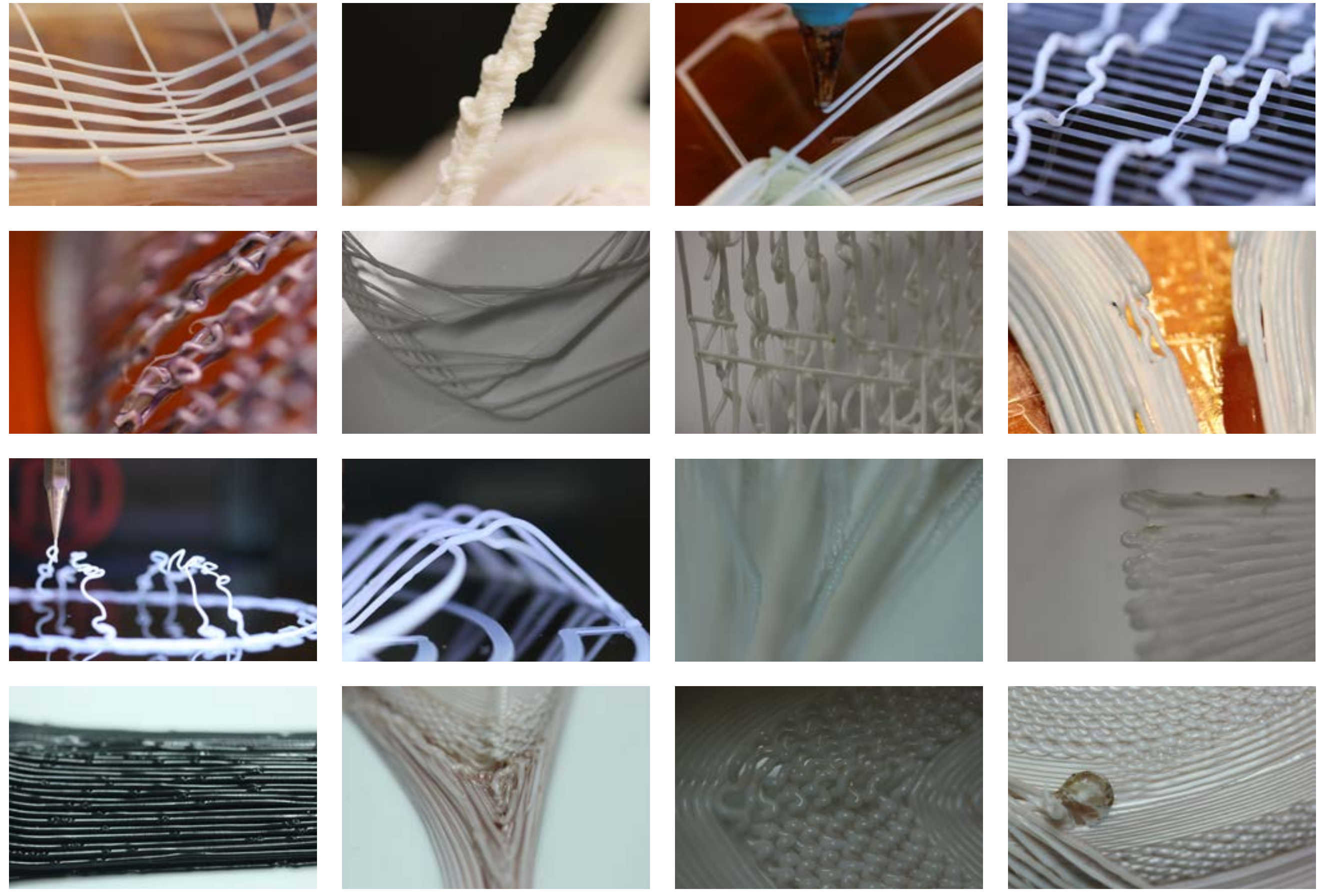


Figure 147. Author, Print Failures

Technical/Physical Limitations

The process sought opportunities to repurpose the contexts and abilities of AM. By shifting away from automation, the research showed that new possibilities for improvement presented themselves, however, there was a risk of reduced reliability. Figure 147 expresses a small sample of the many print fails that occurred during the research.

Generative methods largely aided the creation of models which were found to be both editable and adaptable relatively easily. The main hindrance became the limited capacity of the self-made computational scripts. Advancement within the digital realm would be beneficial for greater interpretation between curves, motions, and manufacturing information.

A system in aid of a more transient step between individual curves, and a single path would be largely valuable. Also, the integration of systems that are able to define motions, without extrusion. This generally requires reverse extrusion to quickly stop and extra material from oozing out.

Improvement would also be found through higher intricacy of the relationships between curve geometries and their correlating extrusion and speed rates. In this research primarily two relationships were defined. One for planar, supported printing, and one for freeform movements. Advancement of these relationships could increase print time and improve deviation of material from its digital delineation. For example, speeding up over spatial areas that are supported by existing geometry, and dwelling over tight corners.

These computational limitations were often manually controlled or adapted. The physical limitations however, were more obstinate. The physicalities of the extruder and tool heads had to be carefully considered to avoid collisions with printed geometry. Compared to the Makerbot, the MendalMax increased spatial freedom due to adaptations and the set-up of the printer.

These and many other aspects could be largely improved upon with the development platforms for new depositional strategies. Even so, these technologies and methods in the developed state provided capacity for new exploration of freeform 3D printing with increased curation over deposition.

Research Limitations

Material deposition and the delineation of form were impressed by many factors. Required shapes of intended outputs, the aforementioned physical and computational limitations, and industrial design factors were prominent influences.

The interpretation of these influences into digital structures and printed artefacts was largely influenced by the design sensibilities of the author. If the same area was explored through a different design perspective, the discoveries would have differed substantially. Input from the research supervisor and other external parties helped to provide fresh insights for utilisation of the technology and qualities of the designs. The adoption of Designed Deposition and the freeform process by other creative perspectives could further substantiate potential value.

This research sought input from users to engage with the deposition of material, and considered their interaction with the objects towards informed deposition. In the case of this study, the author adopted the role of the user, or made assumptions about user preferences. As aforementioned, deposition was largely imparted by using the author's design values. Lack of gaining a range of perspectives from potential users through testing and feedback became a limitation for the full comprehension of user sensitive design. The implementation of user feedback would improve validation of choices.

FURTHER RESEARCH

Future Development

Technical and physical development became seen as the primary area for future research to note. Through this evolution, there may become more tools for deposition and allow for more applicative values to be discovered. Specific areas to develop upon may include;

- Material research; creating, developing, and blending new materials seems of great advantage to the area. Development of self-supporting and fast setting substances with structural improvements would rapidly increase the feasibility of this process towards end product production.

- Exploration of multi-material prints for to allow provision for increased opportunity for multi-functional outputs with increased range of materialities.

-The greater complexity of toolpath creation strategies and manufacturing information scripts to increase the ease of creating structures and geometries.

- Integration of finite element analysis (FEA) into the process could be a valuable technological resource for the deposition of material. This provides increased consideration to the sustainable use of time and material, and for justified placement of the structure.

- Upscaling and experimenting with the implications during an increase in size.

Further Applications

Designed Deposition takes away the security of layer-based techniques meaning for more specific and less inclusive outcomes as rapid prototyping. Even so, it could still be host to a large range of output opportunities. This research attempted to present a range of possibilities for Designed Deposition through a small handful of contexts and application. Throughout the duration of the study, alternative opportunities were also considered, as well as further development of current areas. Within realm of the small-mid scale industrial design context, the following areas could also become appropriate uses of the process;

- Full-scale Furniture - Creation of furniture at full scale, such through the proposed Application Experiments 3A, 3B &3C, and the development of mid-scale designs found if printing at an increased scale.

- Lighting - With the focus on the effect of toolpath and material deposition and density, interesting effects could be found to impact light quality. Clear materials could be utilised as light pipes/paths.

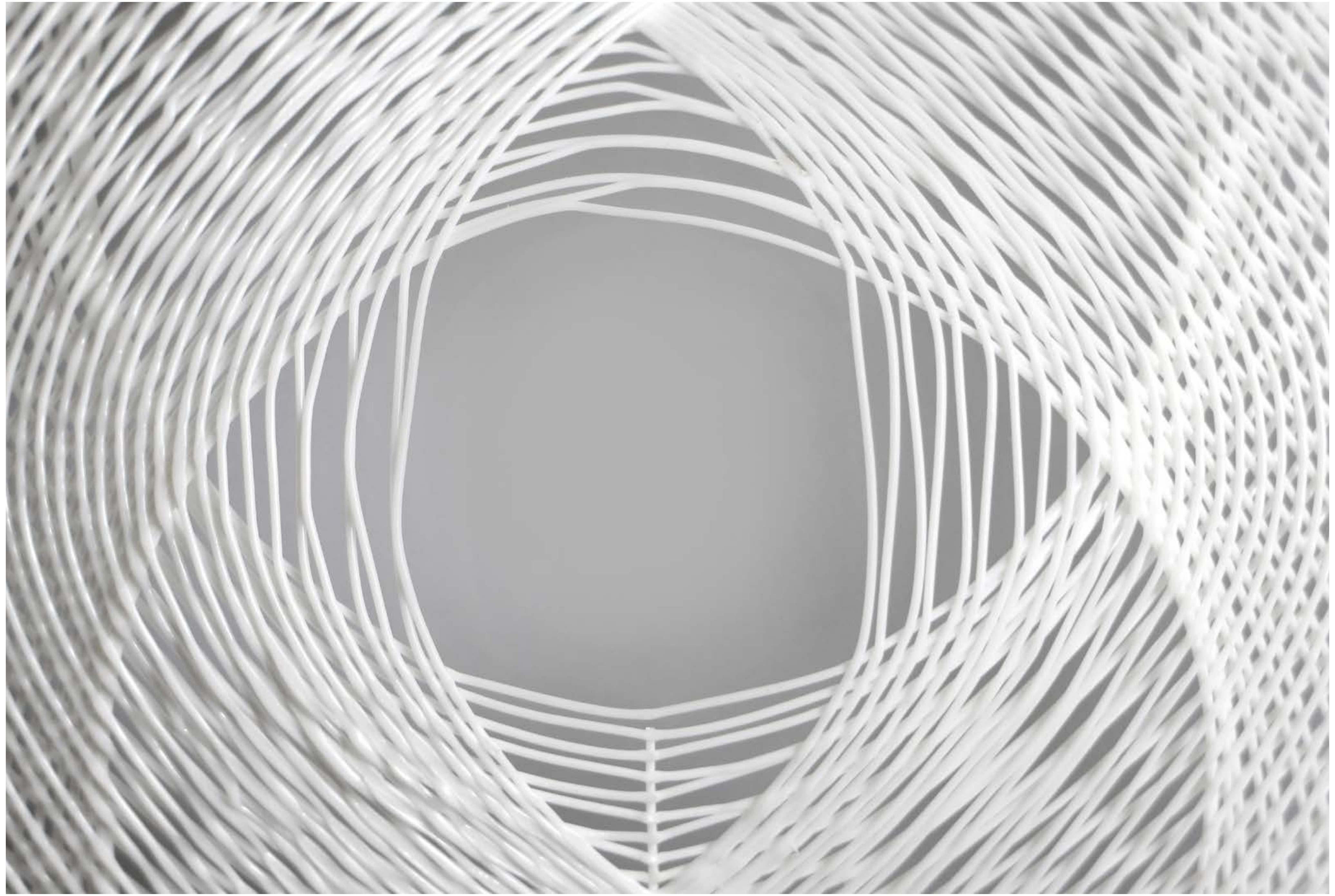
- Exhibition Equipment - The scalability of the process could see bespoke and responsive stands, hangings or surfaces that could be informed by both intended context and exhibited works.

- Signage or Branding – The process could be used as a new approach to creating bespoke signage or branding, which often uses subtractive methods such as laser or waterjet cutting. This process could allow for greater ease for 3-dimensionally considered signage, window exhibitions, or advertising that relate and embrace brand identities.

CONCLUSION

With traditional 3D printing technologies, design ideation is predominantly developed into solid forms. This solid is then translated into the printer's native language, points, motions and speeds. It is through understanding this language that a designer can become an informed mediator between the digital and the physical. Through designing deposition instead of solid forms, quality is not lost in translation. The revitalised communication with this technology is now embraced as a tool for digital craft. Designing through curves that directly translate to printed geometry, great control over the printed expression was gained. Self-supporting material and fully utilised spatial motions were tools necessary to realise material deposition considerate of the method of making and its implications for aesthetic, structural and tectonic value. Consideration of form, intended use and intended user interaction of an artefact are designed concurrently with deposition. This thesis Illustrates a novel direction for the development of bespoke, user-customisable AM products.

> *We may now be in a position to think about the origin of a form and structure, not as something imposed from the outside of on an inert matter, not as hierarchical command from above as an assembly line, but as something that may come from materials, a form we tease out of those materials as we allow them to have their say in the structures we create (DeLanda, 2004, p. 21).*



LIST OF FIGURES

All figures not cited here have been produced by the author

3D Printing Materials Conference. (2017) 2017 Conference Home Page. Retrieved September 29, 2016, from https://www.3dprintingmaterialsconference.com/2017-2/

Ai Build. (2016) 3Dp Technology - Affordable Large Scale 3D printing. Retrieved July, 2016, from http://3dp.ai-build.com/

Alfredo Haberli. Talk a Line for a Walk, Armchair. Armchair, 2003.

Angioni, E., Cabiddu, F., & Di Guardo, M. C. (2012). Value-co-creation through multichannels distributions: The Nike ID case. In Information systems: crossroads for organization, management, accounting and engineering (pp. 259-266). Physica, Heidelberg.

Atkinson, P. (2010). Boundaries? What boundaries? The crisis of design in a post-professional era. The Design Journal, 13(2), 137-155.

Bak, D. (2003). Rapid prototyping or rapid production? 3D printing processes move industry towards the latter. Assembly Automation, 23(4), 340-345.

Bermejo, M., Matei, R., Bek-Bulatov, V., Chen, L. (2016). Growing Systems. Retrieved October, 2016, from http://www.archdaily.com/793054/aa-school-of-architecture-designs-adaptable-structural-plastic-3d-printing-method

Branch Technology. (n.d.). Cellular Fabrication. Retrieved July, 2016, from http://www. branch.technology/.

Budig, M., Lim, J., & Petrovic, R. (2014). Integrating Robotic Fabrication in the Design Process. Architectural Design, 84(3), 22-43.

Budig, M., Lim, J., & Petrovic, R. (2014). Integrating Robotic Fabrication in the Design Process. Architectural Design, 84(3), 22-43.

Creswell, J. W. (2013). Research design: Qualitative, quantitative, and mixed methods approaches. Sage publications.

Del Campo, M., Fure, A., McGee, W,. Manninger, S., and Flexer, A. (n.d.). Autonomous Tectonics - a Research into Emergent Robotic Construction Methods. Taubman College of Architecture and Urban Planning, University of Michigan. Retrieved from Academia: https://www.academia.edu/10073252/Autonomous_Tectonics_-a_research_into_emergent_robotic_construction_methods.

DeLanda, M. (2004). Material complexity. Digital tectonics, 14-21.

Disney Design Studio, RMIT Architecture, Del Campo, M. (2015) Hybrid Phantasm. Retrieved July 29, 2016, from https://disneystudio3.com/.

Dormer, P. (1997). Craft and the Turing Test for practical thinking. The culture of craft, 137-157.

Eilouti, B. H. (2009). Design knowledge recycling using precedent-based analysis and synthesis models. Design Studies, 30(4), 340-368.

Festo. (2016) 3D Cocooner, Bionic Lattice Structures From The Robotic Spinneret
Retreived from https://www.festo.com/net/SupportPortal/Files/426765/Festo_3DCocooner_en.pdf.

Frankel, L., & Racine, M. (2010, June). The complex field of research: For design, through design, and about design. In Proceedings of the Design Research Society (DRS) International Conference (No. 043).

Galjaard, S., Hofman, S., Perry, N., & Ren, S. (2015). Optimizing Structural Building Elements in Metal by using Additive Manufacturing. In Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2015.

Gramazio Kohler Research & ETH Zurich. (2015) Iridescence Print. Retrieved August, 2016, from http://www.gramaziokohler.arch.ethz.ch/web/d/forschung/296.html.

Gramazio Kohler Research, ETH Zurich (2012-2016). Mesh Mould. Retrieved October, 2016, from http://gramaziokohler.arch.ethz.ch/web/e/forschung/221.html.

Gramazio, F., Kohler, M., & Oesterle, S. (2010). Encoding material. Architectural Design, 80(4), 108-115.

Hack, N., & Lauer, W. V. (2014). Mesh-Mould: Robotically Fabricated Spatial Meshes as Reinforced Concrete Formwork. Architectural Design, 84(3), 44-53.

Hack, N., & Lauer, W. V. (2014). Mesh-Mould: Robotically Fabricated Spatial Meshes as Reinforced Concrete Formwork. Architectural Design, 84(3), 44-53.

Hanington, B., & Martin, B. (2012). Universal methods of design: 100 ways to research complex problems, develop innovative ideas, and design effective solutions. Rockport Publishers.

Harrop, P. (2004). Agents of Risk: Embedding resistance in architectural production. Retrieved September, 2016, from http://www.ocular-witness.com/wp-content/uploads/2011/03/agents_of_risk.pdf

Hyunchul, K., Amreen, K., and Xiaolin L. (2014-2015) CurVoxels - Spatial Curves [Portfolio slides]. Retrieved from https://issuu.com/hyunchulkwon/docs/curvoxels_final_portfolio_issuu/c/scbue4v.

Industrial Design Society of America (2016). Retrieved August, 2016, from http://www.idsa.org/

Jiang, N., Wang, Y., Ahmed, Z., and Chen, Y. (2014) SpaceWires by Filamentrics, GAD/RC4 - Computational Design Methodologies for Large-Scale 3D Printing. Retrieved September, 2016, from http://www.creativeapplications.net/environment/gad-rc4-computational-design-methodologies-for-large-scale-3d-printing/.

Johnston, L. (2015) Digital Handmade: Craftsmanship and the New Industrial Revolution. London, Thames & Hudson.

Joris Laarman Lab. (2012). MX3D Resin. Retrieved September, 2016, from http://www.jorislaarman.com/work/mx3d-resin/

Joris Laarman Lab. (2014). MX3D Metal: Dragon. Retrieved September, 2016, from http://www.jorislaarman.com/work/mx3d-metal/

Leach, N., Turnbull, D., & Williams, C. J. (2004). Digital tectonics. Wiley.

Lia (2014) 3Dp Filament Sculptures. Retrieved July, 2016, from https://www.liaworks.com/theprojects/filament-sculptures/

Lobser, D. (n.d.) Vessel – Experimental G-Code. Retrieved September, 2016, from http://www.dlobser.com/Vessel

Martin, (2014). Product design - The Complete Guide. Retrieved August, 2016, from https://www.cleverism.com/product-design/

Matières Ouvertes (2013) Matières Ouvertes. Retrieved September, 2016, from http://collectiftextile.com/matieres-ouvertes/

Matter Machine, (n.d.) Matter Machine. Retrieved July, 2016, from http://mattermachine.com/

Menges, A., & Knippers, J. (2015). Fibrous Tectonics. Architectural Design, 85(5), 40-47.

Milton, A., & Rodgers, P. (2013). Research methods for product design. Laurence King Publishing.

Mueller, S., Im, S., Gurevich, S., Teibrich, A., Pfisterer, L., Guimbretière, F., & Baudisch, P. (2014). WirePrint: 3D Printed Previews for Fast Prototyping.

Nike, (n.d.) NikeID. Retrieved December, 2016, from http://www.nike.com/nz/en_gb/c/nikeid

Norman, D. (2016). The design of everyday things. New York : Basic Books

Oxman, N. (2010). Structuring materiality: design fabrication of heterogeneous materials. Architectural Design, 80(4), 78-85.

Oxman, N., Laucks, J., Kayser, M., Tsai, E., & Firstenberg, M. (2013). Freeform 3D printing: Towards a sustainable approach to additive manufacturing. In Bartolo, H et al., Green Design, Materials and Manufacturing Processes (pp. 3-30). Retrieved from https://books.google.co.nz/books?hl=en&lr=&id=SQlOUkGd_F8C&oi=fnd&pg=PA479&dq=Freeform+3D+Printing:+Towards+a+Sustainable+Approach+to+Additive++Manufacturing+&ots=Gm-Ww6lWXGN&sig=xBmWB4x6HiPDgDTO5_Z_7JXQFbI#v=onepage&q&f=false\

Oxman, R., & Oxman, R. (2010). New structuralism: design, engineering and architectural technologies. Architectural Design, 80(4), 14-23.

Page, J. (2014) Topolabs: God Does Not Build In Straight Lines. Retrieved July, 2016, from https://3dprintingindustry.com/news/topolabs-god-build-straight-lines-26018/.

Paninsky, R (2016) X-Ray Vault Series. Retrieved September, 2016, from http://www.ritaparniczky.com/vault-series/

Peeters, M. (2014) Super Flowers (drooloop flowers)- customizable. Retrieved July, 2016, from http://www.thingiverse.com/thing:240158

Pye, D. (1968). The Nature and Art of Workmanship. London: The Herbert Press Ltd.

Read, H. (1966). Art and industry: the principles of industrial design. London : Faber

Rosenkrantz, J. & Louis-Rosenberg, J. (n.d.) Nervous System. Retrieved July, 2016, from http://n-e-r-v-o-u-s.com

Ryan, V (2005-2009) Factors That Influence Product Development. Retrieved August, 2016, from http://www.technologystudent.com/joints/prddes1.htm

Schumacher, C., Bickel, B., Rys, J., Marschner, S., Daraio, C., & Gross, M. (2015). Microstructures to control elasticity in 3D printing. Retrieved October, 2016, from https://www.disneyresearch.com/publication/microstructures/

Silkworm. (n.d.) Project Silkworm - About. Retrieved September 29, 2016, from http://projectsilkworm.com/about/

Simplify3D. (2017) Simplify 3D Home Page - The Experts Agree: Software Matters. Retrieved September 29, 2016, from https://www.simplify3d.com/

Soni, A. (2015) Importance of product design and factors affecting it. . Retrieved August, 2016, from https://www.slideshare.net/104iiminternship/why-is-product-design-important-and-what-factors-affect-a-good-design-4961483

Spuybroek, L. (2011). Research & Design: Textile Tectonics. NAI Publishers

Stratasys Direct Manufacturing (2015) Trend Forescast - 3D Printing's Imminent Impact on Manufacturing. Retrieved from https://www.stratasysdirect.com/content/pdfs/sys_trend-forecast_v10.pdf

Tam, K. M. M., Coleman, J. R., Fine, N. W., & Mueller, C. T. (2016). Robotics-enabled stress line additive manufacturing. In Robotic Fabrication in Architecture, Art and Design 2016 (pp. 350-361). Springer International Publishing.

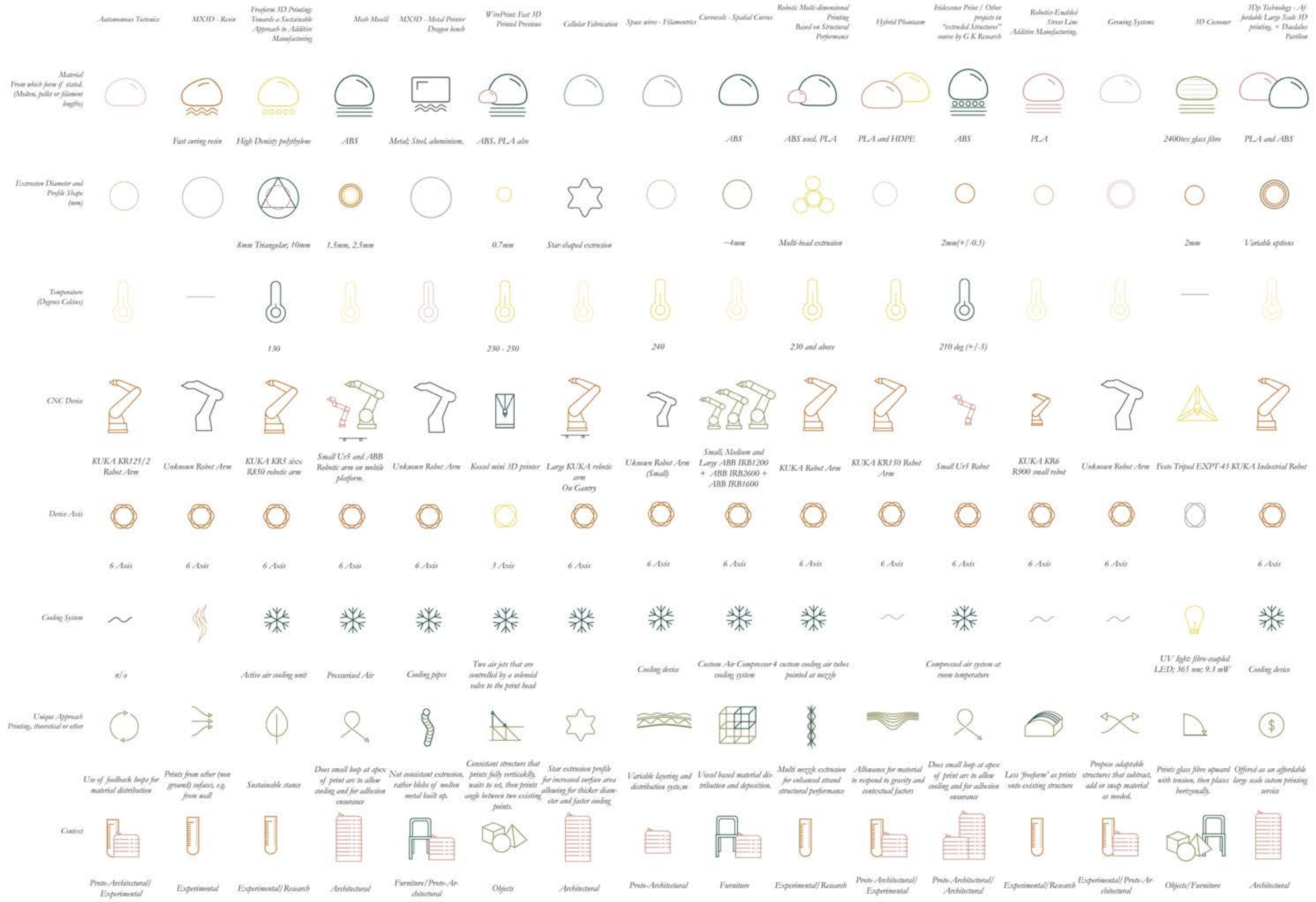
Yuan, P. F., Meng, H., Yu, L., & Zhang, L. (2016). Robotic Multi-dimensional Printing Based on Structural Performance. In Robotic Fabrication in Architecture, Art and Design 2016 (pp. 92-105). Springer International Publishing.

APPENDIX A

Precedent Research Matrix

APPENDIX B

Precedent Technical Factors Infographic



DESIGNED DEPOSITION
Freeform 3D Printing for Digitally Crafted Artefacts

Isabella Molloy