DESIGNED DEPOSITION

Freeform 3D Printing for Digitally Crafted Artefacts

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A ninety-point thesis submitted in fulfilment of the requirements for the degree of Master of Design Innovation.

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#### ABSTRACT

Through the exploitation of new additive manufacturing (AM) Bespoke computational processes work to encode material expressed.

'freeform 3D printing' is an AM method which builds through the opportunities. deposition of material that solidifies upon extrusion. The result is free-standing material forms with diminished need for support Among other things, the research-through-design process material.

on layer based techniques that are built from ground-up. Instead, through an industrial design perspective. motions can move simultaneously in the x, y and z axes. This increased freedom of motion allows the designer to disregard Through iterative abstract and application based experiments, to the design of artefacts, specific approaches that consider both towards the creation of digitally crafted artefacts. form and material deposition concurrently allow the authorship of the method of making to be reclaimed.

processes, this research seeks to reinvent the designer as an deposition with qualities that are tactile, visual and expressive informed mediator between the digitally defined and the physically 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 Current 3D printing techniques generally construct an object layer three-dimensionally informed and considerate of the integral by layer, building vertically in the z-axis. Recently developed, nature of its making method and its output, exposing new design

suggests how parametric modelling could be used for masscustomisation and suggests a possible path for AM beyond Building in this spatial manner means that AM is no longer reliant prototyping, towards the manufacturing of bespoke products

the requisite that solid forms need to be delineated prior to Designed Deposition pursues an increasingly integrated process considering material deposition. Considering this in relationship between the user, the designer, the digital and the physical,

## 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*

I would like to first give thanks to my supervisor

Tim Miller for his ongoing guidance and input
throughout my studies and unwavering investment in

my work and this project.

My family, for the encouragement to persevere with my studies.

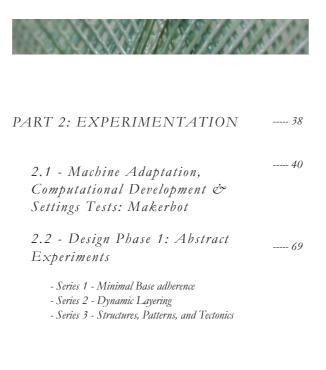
Patrick, for the immense support and encouragement.

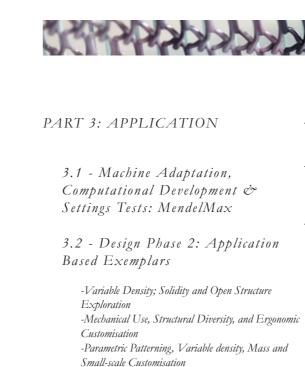
Anna, Sam, Kalen and Adam for keeping the year light-hearted and my spirits high.

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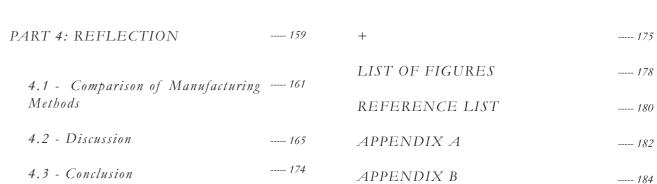






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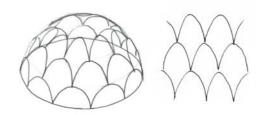


Figure 1. Author, Common 'banding' or 'space-frame' methods used by many freeform precedents



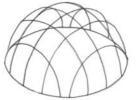


Figure 2. Author, Simple example of proposed Form Responsive

## INTRODUCTION

Freeform 3D printing provides opportunistic capacity for new These defined by automated dispersing algorithms become an industrial design perspective, this research will explore how approaches to building additive 3D forms. Currently, one of the reflective of the traditional slicing processes, building ground-up. this 'Designed Deposition' can develop extrusion based printing main types of additive manufacturing (AM) is fused deposition This research endeavours to take intended forms and structures methods beyond rapid prototyping. modelling (FDM). This method melts and extrudes filaments of into consideration from the onset, informing bespoke material printing material, most commonly thermoplastics through a fine deposition differentiating the process from any automated, CNC technologies with both 3 and 6-axis of motion present print nozzle and deposits thin layers of material that build up to banded or layering methods. form 3D geometries. Freeform 3D printing retains parent novelties Resourcefully designed, the path the print head follows can built form. become increasingly economic in material use and printer movements, as well as reduce post-print clean-up.

architectural. These projects often look at large-scale building deposited. The FRM poses opportunity for embracing functional, and energise the material..." (Leach, Turnbull and Williams, 2004, solutions for complex structures, taking a structural space-frame aesthetic and tectonic applications of material, prospering upon p.142) approach in creating three-dimensional printed forms (Figure 1). the predominantly structural pursuits currently in the field. Through

from FDM printing, using the same computer numerical control Figure 2 illustrates the form responsive method (FRM), which fully use of robotic arms with 6-axis of movement, by comparison, this (CNC) machine capabilities in conjunction with material extrusion utilises simultaneous x, y and z axes movements with regards to research uses standard 3-axis FDM printers. The capability of CNC to build 3D forms. No longer relying on planar layering techniques. the intended form. FRM disregards the requisite that solid forms machinery for custom creation separates it from the homogeneity Instead, it employs self-supporting build material that solidifies need to be delineated prior to considering material deposition. of mass manufacturing (Bak, 2003). Through the use of generative upon extrusion to create free-standing material strands in space. Instead, artefact specific approaches will be used to consider processes, user customisation is viable. Users could be allowed These are generated from the toolpath of the CNC machine which both form and material deposition concurrently. Artefacts are the opportunity to adjust defined aspects of artefacts on a broad exploits the freedom of simultaneous x, y and z axes movements. now fundamentally defined by repetitious lines used to create a and locally oblivious scale, such as with Nike ID (Nike, n.d.). Through this process, the need for support material diminishes. toolpath which determines the geometries of three-dimensional Through parametric modelling, user customisation capabilities are

techniques allows for exploration of the new opportunities that the designer, the digital and the physical, exploring"...capacities of Current applications of freeform 3D printing are dominantly proto- come with gaining greater control over how material can be new tools and techniques to emancipate form, liberate structure,

unique benefits and hindrances as a tool for spatial printing methods. While most research to date is conducted through the explored in the creation of bespoke AM products.

Evolution beyond traditional layering or common banding. This research pursues an amalgamated process between the user,

# TERMINOLOGY

#### DIGITAL FABRICATION TERMINOLOGY

## 3D printing:

The process of making a physical object from a threedimensional 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 semimolten filament, the material is deposited on a layer-bylayer 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 coordinates 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

M83, use relative distances for extrusion

92 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

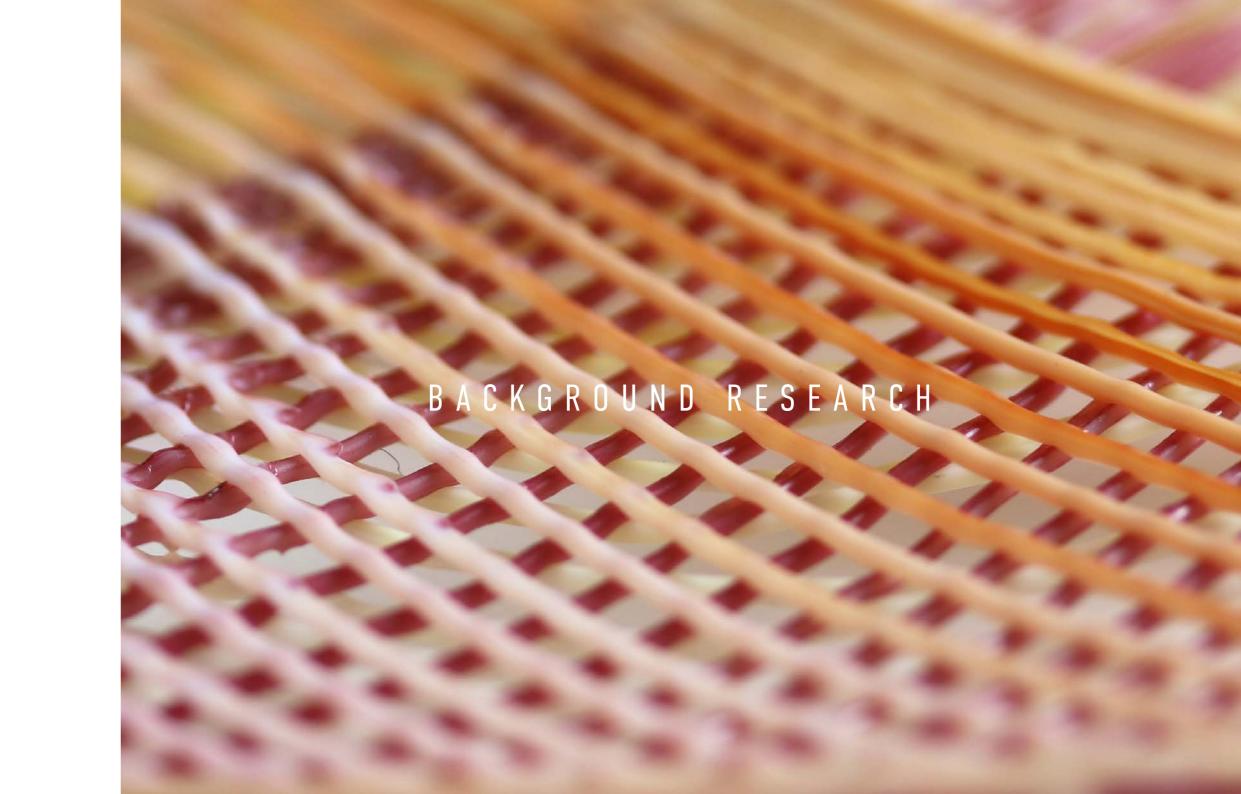
## Craft / Digital Craft

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.

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# PART 1

1.1 - LITERATURE AND PRECEDENT REVIEW

## ANALYSIS OF EXSISTING PRINTING TECHNIQUES

Materials, machinery and software are largely consistent In-depth research was undergone into current freeform techniques throughout current precedents. However, with varying focuses and findings. From this information, a matrix was developed to towards the use of the technology, the articulation of the freeform further understand unique, comparative, and discrepant factors printing method is diverse. They range from being strikingly of a representative sample of spatial printing projects. Included experimental in their use of materials, making, and computational are projects which were closely aligned with the research pursuits utility, to being heavily application, construction or technically at the time of investigation (July 2016 - May 2017). The matrix focused.

Freeform 3D printing has mostly identical physical requirements analytical matrix use simultaneous x, y and z axes movements and to FDM printing; a CNC device and an extrusion tool. So, while extruded material. it doesn't require many further advances in AM's physical technology itself, it does require a revised and open-minded The upper categories explore settings, materials, and other consideration to how we approach 3D printing as a manufacturing technical information available towards their achievements. method. The spatial freedom removes the security of layer based These will be constructively considered during similar technical methods that can take nearly any geometry and make it printable setups of the computational and practical development stage. through upward growth, allowing the process to be customised The remaining categories of the matrix are collated information in and uniquely considered in relation to desired qualities.

projects and precedents become vital to gain an understanding contexts were also researched and subsequently included within of the field. In the realm of a new method of making, technical analysis and discussions. 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).

illustrates an overview of these findings, seen in full in Appendix A, with a visual reference seen in Figure 3. All projects in this

regards to all relevant theoretical, contextual, and general findings or implications, which are discussed in the literature review and Research of the triumphs, holdbacks and implications of existing throughout the thesis. Less specific projects in further reaching

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Reefurn Schnique	Same Sanding type approach.	siner cover, growing vertically florizontally.	Multi head extrusion freeform secs.	Banding - Parallel webcallaging counters: with connecting coard between	Small amounts of notice metal act a time, to print double curved lines in mid air.	Resing	Booking	Banding - Space frame but more three-dimensionally explorative	Freeform Works	Multi head extrusion freefams secs.	Layenel. I would call in between of traditional FOM and freeform printing.	Banding-	Simultaneous layering on supporting ourface.	Variable, combination of human input, material freedo and rabotic extrucion.	The Standing in only straight lines.	Randing Shirty consistent layering dimensions:
the of Publing' two darks coulding	None-sets the roterial form conscaling and respond to gravity	Notices to the line is being clowly already by specification and deling of mention is placed on the personal year of the deline of the control of the personal year of the year of y	in fairly statistic freelaned and eratic - not much pulling / the Service of Obs.  Design of Obs.  Sec.	Stopping at a park of triangles indicates it was longer time coping in that position for cooling below changing direction.	Not much as the law is built up closely almost in layer, which a small dailing of execution in gloced as as the periodicy sectional and closely execution, in larger year the principle sectional and closely execution, in larger years for the principle in a see discharged years for a final period to accommodification of the wheel discharged with the resolution and contact the closely are resolved to the the close	in the off-testion accupant sections is sharp certical, as paged to cost, the sagint are printed in downward in section when costs and end point are specified.	Oncurs - educion in car form relines need for quick cooling during tension - but not talk of or chose explicitly. But seem to prior future on less flucture unsupported allowing for more coolingsteen and one traction between protest and point of excursly white cooling.	tropechel and hard to bell.	tangeofied but overs like little - initially slow printing fore researcizing takes place contently meaning bear bearing weeked and over-curviness religions, can be actived. But later an in research speed opposedly through improved technologies - overlag cooky improved technologies - overlag cooky through 2 motions and 8 heaters.	idde-maids extracted behalf are used to help define position of the line receiving fest tention is needed.	Nonefittle - Less the Hosterial form naturally and expand to gravity - but printed sidways co-excipants are printing floritantally and ittle-vertical motion.	Stopping at a per' of 's langue; indicase; it was langue to stoping in that purifies for cooling before changing direction.	no More—due to sce of mould out freeformed uncupported ctructured require section (rading time whilst extruding flora printer.	Little, is manipulated a birthrough human input and interaction, but propioal suggests use of multiple color areas, and feedback loops.	Econolise and curve, while vertical and under trend on, the fice is pacifies.	an Straight todipaths suggest use of fession. Speaked motion are after vertical, and angles are made down as therein then a set starting of operation light and end point to security the set of the set of the security of th
Contract	Record based autoromous churant experiments.	Significancy (Newsork Stood	Architectural/Design based Research "Applications for this need process are sorted and range from product beharizon or familiare and architectural scale-processing"	tolamically fider canel operal method as evintured concentral namework.	Experimental / Numburo	Fact preview for designent, to allow for iteration before final print. To make capid prototyping made more capid and lower fidelity.	Archinectural Construction *Virtually utilized designs freedon using economical construction methods.*	housest—Computational design methodologies for large-scale 80 printing	Tanying contents - Architectural research background Columns, Chains and stateours exemptified Architectural structures proposed and rendered.	Architectural Research	Signification (Architecture based)	"becauch - Mid ground between architectural performance and criti having freedom of research for newhip and visionary results. "Exhibition space.	Research - technical based for 250 Surbox.	Experimental proto archimoture with intention of archimotural	Experimental leading to product production.	sage scale 82 printing for anyone interested in using 82
54è	Mászie- epeinetáljusachhoszá.	śrad (hid szár Saprimerzi / produc szár	Md/large mid stale-experiment but intended for large architectural scale-application.	Mid/Lings- proto-architectural / architectural	Military Large bench	Small scale product (desiras) primer scale)	large architectural	Middlarge Printed sid stale, and pined to become puto-architectural stale	Mid proto-architectural / Furniture	Mid/large and scale experiment but intended for large architectural scale application.	Mid-scale prote-profriences/al-current	large Architectural	Small Small text scale with intentions of larger scale application	Mid - Carge scale - protearchinectural	Small/Mid Product scale intentions but currently small ship intin scalinits	Mid-Cange coale- g Architectural, Proto-architectural, and when in callab wi Zaha wadid besign, furni turu.
Cains of efforestiation	Advantage of the second of the	"This method makes it grounder to create the algorithm on any given earling our first, independently of its accommission and constitution, and with flowers need of additional and appeared makes," the property makes the analysis of makes."	"Name" and the additional design approach for the printing without additional formation approach to addition to encode configuration of the additional to additional to encode configuration for the additional configuration of the additional to extend the state of the additional to extend the additional to encode the additional to encode the additional to encode the additional to the addit	Main, for equipment of statutes acceptance, who descrip, Albertale connection to connectional flamework.	For the force of the control of the	Number facilities and a requirement interp, but for organization providing as their providing continues and an account based. On each attent any fore granulae.	Natural bull & customably and efficiently.  Materials are as a present a customath.  Completely in the in a mount and half of the any and worker.  I was already the complete and a comple	"Valuements intends to overside the formal intentions of quite flavors, existing to intended the formal production of quite flavors, existing to ensure the continue of the continue and the light digner ensures in the continue and exist in large dark existing and the large color existing a relatively of our period of time."	Yeard based	Structural option contains and anguing technical analysis to shape as different anguing technical analysis as the design requirement. Space with informed existinate extruction				Total d'autople robots. Suggessed ability d'adappailler, over tranç la censor au- papiet avigité soine material. Allowance for the source) behavour of the especial.	nd Shif product production.	corp ccare building studies for critishands of a set proper content of a state of printing of Pickas of a abujum rest and a state of printing of Pickas of a deligner rest and a set of the set of the set of the state of the set of the set of the set of the set of the set of the set of the set of the set of the algorithms, and an Scale state of the algorithms, and an Scale state of the and the set of the set of the set of the algorithms, and an Scale state of the and the set of the set of the set of the and the set of the and the set of the and the set of the and and and and and and and and
Native directions (face works / Other propriet	Administ School I	The project is present to MMID Motor Private	Moniny Calif. Course lace of deep compays receiving a way bear the second control of the contro	Compay to the development of both material studies proclaimed, required by aging protections, companing by aging protections, companing and another proclaimed and applications are controlled and another proclaimed another proclaimed ano	MATO and it pyrind high is known by marked as years being in the pulse in the pulse of the pulse	The factor work, we given to engine how for 10 granting allows for one of gas elements on the counter factor of the property of the counter of the counter of grant and one of physical filt for counter of grant and one of physical filt for counter of grant of the counter of grant of	Subliquement of the Young budget, National and State (Market Parket Nation to 2007)	properted.	properfied	Nutine second will be conducted a under to spigin this counterperformance centred unto demonstrate printing company and because the content printing counter second of princip second counterper for their second of princip second counterper for second counterperformance their second counterperformance to second counterperformance second counterperformance contention of the counterperformance contention counterperformance contention	Above further and part for purpose.  Mentioned princing the connections in a conduct topwed pointing process for comparison.	Other experimental cassage of freelines entraction pro- cessing of what terms to be a cause of last freeling of the cause of last freeling of the cause of other high cause of laster research.	*Continue to investigate dia secondi and completibilities of inchedup placed using the laboral **Secondata and improve the REM production to a bending **Secondata and improve the REM production to a bending **Develop a computation of transvers the assessment **Develop a computation of transvers the assessment **Develop a computation of transvers to assessment **Develop a computation of transverse to a secondata and **Develop a computation of transverse and **Develop a computation of	# hit persist further proof of a society and development of	; Proposed design of "ther"	ougusted
	first oit of depositions selecting the points with the highes		These is tractivistic mendicating and more effective deploy processor. To significancing agond content of a security processor. To significancing agond content of a security processor. The significancing of Administration of the significancing agond agond to significancing agond agond the significancing agond agond the significancing agond agond the significancing agond the significancing agond the significancing agond the significancing agond agond the significancing agond agond agond the significancing agond agond agond agond the significancing agond	CALUM CAP TO COLUMN			Tredut.			12 technology for from medicar the requirements of	and recording on which.				(in. Substantings of Viscout' opining.  10 Extension of Contract o	Way speaker, are of firm that cappe are of distributes and approximate the cappe are of distributes and approximate the cappe are of distributed and deep speakers. The capper are capped and approximate and a deep speakers. The capper are capped and approximate and approximate and approximate and approximate approximate the capped approximate and approximate approx
bee	To community regions up the community and not of forming or the resulting which collisies formed as good to appear to specify draws, and many the collisies of	"Salida 20 luyer, that are grown to the manuser file algor, the littinum can fallen each "Supervision con algoritic are grown and "Supervision con algoritic are grown and seators of a salidation of supervision and seat for additional supervision for a	"salid based is given, to epimizate of execution of execution of execution of the execution	"the advant and knowley in its invention and affects appending one sign constraints parts be depresent the invention and an appearance of the properties of a constraint of the properties of a constraint of the properties of a constraint of the threads—one one region for the constraints of the properties of the constraints of sections of the constraints of sections of the constraints of sections of the constraints."	For the first see we can bit principage collections on the first segment growing controls."	Then though considered a cycly crosspage task, to printing as to the first a mountain cost disperience printing as continued and compared to the compared to the compared to the compared cost, and the cost of the co	content of which desired control or mession are supplied powers from the control of control or cont	"As artificits, we can design for inflato menutions and enemy of inflamentary, controlling the deposition of a control of inflamentary, controlling the deposition of the inflamentary of the inflamentary of inflamentary controlling the media configuration for inflamentary controlling the media controlling the inflamentary controlling	"This areasts, which has an error do faircition for pression digital architecturals or notice and has accounted top in depth and faircition and out dates must be sailtric comes are architectural." "Small the report of the molecular architectural "Small the report of the molecular architectural architectural architectural architectural architectural architectural architectural architectural."	study the consorter approach is become control assignment and control and cont	"Nozal y si fe sancii îngod dut ya ca poducii Shighti monimer." Shighti monimer." 'Yea si mo dife earchi Sariya ca no riche fast dega pedacirile fast principal can order fast dega pedacirile fast principal can order fast posta sufficie fast principal fast sufficient principal description of the sufficient principal fast or excessed."	"Safe amount of market in updated on a black of a financial with different inforcer colors." "Safe design which is completely programme to accommodate while particles and "accommodate while particles and".	Calif "year to a delicer name durating" (SAME, "The proposal normal address as integrated another both and the california and proposition and the california and th	The opposition of the respective sea in large mode management of the control of the control of the detection of the control of the detection of the control	Transista escaria cada e se fesidas prasac- caria que lleida de Sciusios de nos de legiga de propinsi quelle de Sciusios de nos de legiga de propinsi quelle de sideo de la companio de la se destrucción de la companio de la companio de la sede de la companio de la companio de la companio de la companio de la companio de la companio de la companio de la companio de la companio de la companio de la companio de la companio de la la companio de la companio de la companio de la la companio de la companio de la companio de la la companio de la companio de la companio de la la companio de la companio de la companio de la la companio de la companio de la companio de la la companio de la companio de la companio de la la companio de la companio de la companio de la la companio de la companio de la companio de la la companio de la companio de la companio de la la companio de la companio de la companio de la la companio de la companio del la companio de la la companio de la companio del la companio del la companio del la companio del	out "Novineign auch if he has" "Provineign as Shorousing to Marking the Assess of purchase for a seal-factor of the Assessment of the Asse
Opportunities he refull information is finitelizably to my thesis	Setting the numerical and process inform direction. Similarcing viscosity of numerical act well as designing it.	Intending munificities cathing funct allows the print be guissett to also purfices. The design material. Printing from which glaves rather than youth ground intending and could have unique printed al.	to the different disorders of the council is nutricional; both will clear to have some supportion from drying a standard and come clower-better founding sections.	Discussion about onthe descript and differentiation from perfoliations is oriented.  Movement travelst, curtation and differentiation releasest outside intentions.	transacting resolitors in casing start a filescate-print begareasts any unface.  Ethelf unique resoluting resolution the strength and large-buy of each.	to imaging sick or of free form to printing - no claims that ann't fulfilled and to acquire to a string, and have it work.  Favoring it post with in the country, to the gradient of hybrid by-ring options to involve actuable fidelity sections.	for dapped profile a cleany way to increase diameter for comply without his lefting carding side which is commonted by the increase of without area. They seen to exemplify the most radical curves and charp- direction-changes in prints.	More complex as varying approach to todgeth - order than continently uponed examinals. Insuperblammer form approach.	More canaderation to accided on. Product sole application. Stratation of futures to based Grameter. Strape approach to 5 Welton process.	Technical inflammation like companious of ABS to PAA. Bending and chaning experiments and print crossed disension from trapiate, could be a good companions to how my back compane. Buplications of Restruction Compane. Buplications of Restruction Companion may help inform if it come to customizing large extruder.	uetting nuterials and failunes be of value and embrace curvaliping.	Date of colour to highlight studyon is appending. Storing that you can take the space from down—grind for and in-extrude and create a new form is immensing.	Technical information on others, time glipconnection structurally yellicent forms. Compatibility of the compatibility of the compatib	Suggestion of contre-printing Variable national qualities	Precise an imanitable process so patientially more reliable supports. Supporting the image of the protection and their opportunities - a Straining exected.  Printing vertically as an embraced Sechnique	ble  Use of the process for custom or bespoke large scale printing uption.
Mind south- That may before my Threat	tragularing/Sportaneous ent of process less appropriate for end product production.	Muchy only gaing hardwards (*Vertically No deservant or stary turns need turns and the a limit process.	Providing reserval connecting to plants part previously casined and tendented from of Afficial.  It was also based upon attempting over-rampin path plants pad part participate process that a logic path plants pad part participate process. Set a logic path plants pad part participate participate for much grown featballing in the manuscurability of the evaluate while attacked to the manuscurability of the evaluate while attacked to the manuscurability of the evaluate while attacked to the manuscurability of the evaluate while a participate of the participate of the evaluate and the eval	to the budy type (banding band process.  User claimed jo nech sould rest) to be well. "Digital flat custom focus on the translation of the maturally well polymer band educing process into a fully translating construction system."	Amount till layering in a servertact in ent contact emulian, but smill dan af netal wideld upon the se- tening cill vertically forward, special reducted creation.	E. Strictly banding basel. Little sectheric considerations	Scaffold cavature is considerated ladic options of variation.	Computes stall everythat of ideals for exceed the completing of the final prints) outcomes.	Youlgath is comewhat unruly and could be considered no purposalishy. Described of material. Still a ground -up approach.	PP ABS instead in crowge in neutring bending and shearing book.	traggila sty-potentially binders for creating end product quality-but informative for the active process.	Havingto print in extions. Still showly layer based/landing method. Print quality poorbly slightly lower than other project	New to create required from: SOII as force of layering - although 1 dimensionally flayering. Creation of 84 outhook ordine than 10 objects - hence defining persons as '2.50'	tragularing/Sportanenky of process lacs appropriate & end product production.	or Fairly slow Sill banding Limited to crought-print lines	Still a very consistent algorithm based material dispersi- system, little-emponents form agent from frame morph
Millionard purposes to half late	Station in Nature Caller, the Mean of Economics in National Caller, the Mean of Economics in National Caller, Mean of Economics in National Caller, Medical Coding, National MET Peac 2006, V 2-8	eb.	Ches, printer, will self. 2023 ISS colours for miley more. Modif layer classifier and mechanical properties.	Wiles were: "In the description" pages of an interest pages of the classes and a good for a classes for a good for a goo	AD.	sage reference los artis releases pages.	nja	clin KCL Project in Computational design and making the of Computer	ignorhan-danad tachena ignorano-fainetta [ fardel]	To the project SMITMENS by Advanced institute for Advanced institutes for Advanced institutes for Carbination (Inc.) and Carbination (Inc	Enthod Seepen "Techar demons of an introduce. Securing when is one of the device plane about the law of an introduced control of the about the thin of the analysis of the about the followed key and by American Science.	Mallion, Albati A, Rhalbasi S, E Californi S, Californi Serbasinger, Tries a couch Dec	II, Tavid Oser, T. 2023, Team character approximation for addition ensulfacturing based in principal critical law, followed the control of the control of the control flows of the control of the control of the control flows, the control of the control of the control of the flows of the control of the control of the control in an interaction of the control of the control of the control of the control of the control of the principal control of the control of the control of the control of the control of the control of the flows of the control of the control of the control of the control of the control of the control of the control control of the control of the control of the control of the control of the control of the control of the control of the control of the control of the control of the control of the control of the control of the c	AID.	4/4	Marcial from Dack manufacture, from Seas. NASM GPA for artificial sindigeness integration. And May exposes.

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	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
-Most common is	-Often unspecified	- Curvoxels	- Mostly	- All that specified	- All info unique,	- All but two robot	- All but two using	- Most custom	- Cooling blower/	- All specified used	- Unique per	- Dominated by	- Most output	- Dominantly proto-	- Mainly Mid/large -	Unique - But often	- Mainly specific	- Proof of concept	- Often statements/
ABS, especially	but most appear	(2014-2015) the	unspecified	are using ABS	often technical	arm devices, both	6-axis	made extruders	compressor	a Grasshopper/	project	varying types	focused projects	architectural, but	Mid - mainly proto-	adhere to one of	technical	through successful	claims/ideas
performance	below 4mm	only project to		with heat range of	knowledge	large and small		based on generic	systems in most	Rhinoceros 3D		of spaceframe	used tension by	also experimental	architectural	multiple of:	improvements	projects	exceed outcomes
based project		specify - speed	- Sizing dependant	210-240				3D Printer	unless unspecified			or banding	dwelling at the	usually with	Large - for more				and cheats/
rather than	- Thickest extrusion	was increased	on CNC device			- And when aiming		extrusion nozzles		- Tam et al., of		approaches,	apex of a triangular	architectural	applied/application	- Material/process		- Technical	exaggeration of
experimental	achieved by	over research		-Other		for large scale			-Most using	Robotics-enabled		especially when	form.	backgrounds/	focused	driven		information and	ability is seen
	Branch Technology	by developing		assumptions are;		construction, they		-A small number of	multiple pipes	stress line additive		structural / output		contexts.	architectural			guidance for	
-PLA and HDPE	(n.d.) through star	extrusion		-HDPE much		were mounted on		creating multi-head	directed at the	manufacturing		/ architecturally	- More		contexts	- Technical		successful settings/	- ABS strength
used on few	extrusion profile	technology		lower		a moveable base		extrusion nozzles	beginning of	specified other		based	experimental	- Some technically		Research /		strategies	criticised to be
occasions,				-Metal extremely					extrusion.	programmes of			projects often	/ material research	-A handful of	Optimization			limited in shearing/
mostly for more	- A small number			high heat		- Wireprint the				note (2016)		- Experimental	allowed drooping	focused	small-scale outputs			- Increased cooling	bending forces
experimental	of multi-strand			-Resin no heat for		only project using			-Metal no cooling			projects offered	and used tension		or pursuits, such	- Nature informed /		time through	
projects	endeavours			extrusion		standard 3D printer						more diversity in	less	- few touch on	as Wireprint for	Sustainability		thin extrusion, or	- Size / geometric
						(Mueller et al.,			-Glass fibre using			processes.		industrial design	rapid prototyping			increased surface	restrictions
-Laarman (2012,						2014)			light instead					applications but	(Mueller et al.,	- For novel		area	resulting in printing
2014) also used												- Others had		more structurally	2014)	architectural			in sections
resin and metal									- Resin appears to			structural focus', so		considered		construction		-Conceptual	
									use heat to help			prints were more				method		guidance	-Inconsistencies in
									to cure			research than						from research	material deposition
												output focused				- Computational		based projects	in research-based
																complexity		- embracing	projects, but more
																		imperfections and	unique use of
																		letting material	toolpath
																		drive the designs,	
																		technically driven	-Outcome based
																		or structurally	projects lack
																		focused	material and
																			structural variability
																		- Use of colour for	
																		increased toolpath	

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readability

#### 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)

## Precedent Projects

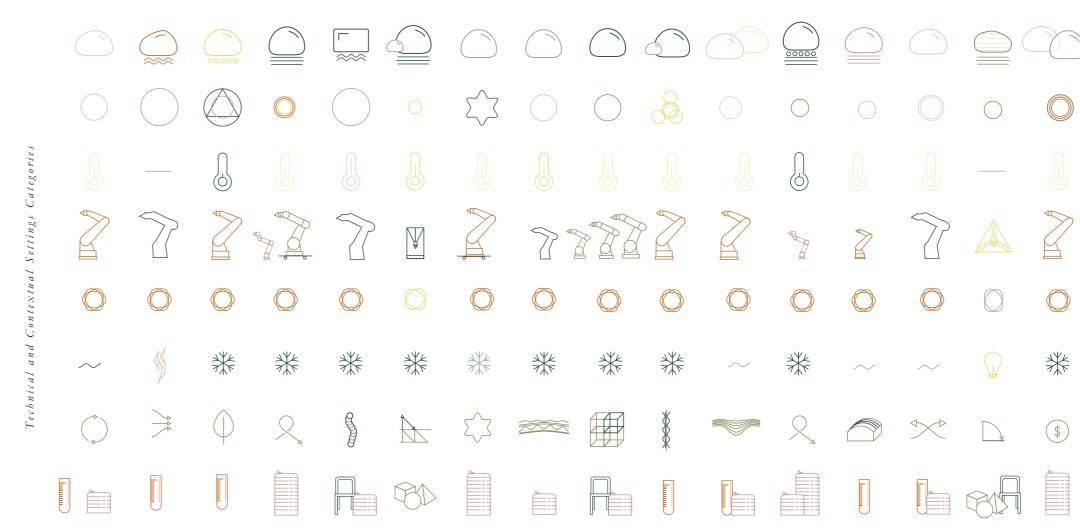


Figure 5. Author, Precedent Technical factors Inforgraphic (Visual Reference)

#### CONTEXT, APPLICATION, AND SCALE



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



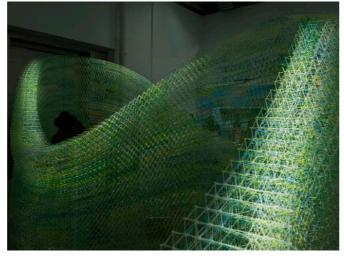


Figure 7. Flotsam & Jetsam Pavilions (Branch Technology & SHoP Architects, Figure 8. Iridescence Print (Gramazio Kobler Research & ETH Zurich, 2015)

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). - Experimental projects, taking a more abstract, Micro and Macro applications of AM are emerging, and freeform materially or theoretically driven approach to the 3D printing is finding popularity towards novel large-scale process 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, - Technically focused projects that research thorsuch as Ai Build (2016) Branch Technology (n.d.) & Gramazio oughly a structural or efficiency based motive with Kohler Research (2015 & 2012-2016). Most of these have been use of 3D extrusion and movements 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 6, 7 & 8equipment. 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.

Efforts are being made to develop the capabilities of additive As a whole, there are three primary underlying contexts and As the freeform process is directly expressive of the toolpath manufacturing technologies for broader applications, scales, and applications of which the projects adhere within one or multiple of; that the printer follows, the digital design of the process and

- 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

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

CONTRIBUTING FACTORS ARRANGED INTO RELATED CONCEPTS

Figure 9. Author, ID Factors Ordered

Figure 10. Author, ID factors Collated

Function Aesthetics

CostMaintenance

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

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

AESTHETICS MaterialsFashion Form Style

Tactility

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

VALUE/ECONOMIC VIABILITY CostMaterials Industrial Production Prestige Value Assembly / Disassembly / Maintenance

OTHERCompany 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 similar methods. Using indifferent slicing systems and approaches A small portion of freeform precedents suggest uses of this settings and speeds.

Ordinarily, the delineation of these is through automated slicing manufacturer. systems. While these slicing systems keep the manufacturing as textures, quality and materiality, giving the appearance of to be of greatest value towards successful design. low-fidelity outputs. In 1968, Pye made observations about the uniformity of mass manufacturing;

craft, and the potential of both. (p.need to find again)

of toolpath and print information for AM, particularly in FDM or when being designed.

Society of America (IDSA) to seek the benefit of both the user to create objects with unique requirements is guarding the ability technology with reference to industrial and product design and the manufacturer (2016). In the case of the manufacturing to consider the material quality of products, and holding it within motives. Wireprint uses a standard FDM printer and its software method at hand, AM, the printer becomes the manufacturer itself. a prototypical realm. Increasingly high-resolution printers are breaks the input form into a wireframe mesh that is spatially printed. The device and process has needs, requirement, limitations, and providing capacity for the creation of 3D printed final products, The creation of this for low-fidelity wireframe printed previews in preferences. A rich understanding of the manufacturing method such as for one-off complex pieces (Bak, 2003). Reclaiming the the early stages of the design process, allowing for guick and allows the designer to become an informed mediator between authorship of material through informed curation of its deposition iterative design processes. (Mueller et al. 2014, p. 273) While the user and manufacturing method. The language between these, could pose an alternate path for developing the process beyond project is within the product scale and context, it doesn't seek to in this case, is q-code, informed by primarily toolpath, extrusions rapid prototyping. This creates opportunities for a conversational use the process for a final product purpose, but rather make AM relationship between user needs, product requirements, and possible to be an even faster rapid prototyping system. Hyunchul the printing process to be of value towards user, product and et al's project Curvoxels (2014-2015) also exemplified outputs

Soni, 2015) were analysed and their information collated into a design perspective towards the use of material deposition for the The failure of mass production is not that it is incapable of hierarchy of factors from the most to least recurrent elements, as benefit of the product, user and manufacturing method being illproducing quality products, but that it has created a system seen in Figure 9. They were subsequently collated by the author explored, this research seeks to find the merits of spatial printing of undifferentiated, uniform, and characterless products; a into groups with related concepts (Figure 10), which became for bespoke industrial design-centred products, with response to material culture which gives little value to workmanship and reflective of the design values stated in the industrial design the researched influencing factors. definition by the IDSA in 2016. These factors were researched to inform the development and iteration of product focused designs. Parallels can be drawn between this statement and the creation Providing specific factors for material deposition to respond to

within an industrial design context, recreating the Pantone chair through a voxel-based printing method. They produced unique method comfortable, they can impede design qualities such A modest analysis was developed comparing factors considered 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 Four sources (Norman, 2016, Ryan, 2005-2009, Martin, 2014 & on structures and forms. With the identification of this industrial

#### PRINTING AND STRUCTURAL APPROACHES



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)

these spatial forms are often built up in 'bands' of spatially printed geometry forming software makes for more diverse structural printable information.

performative purpose.

The premise of freeform 3D printing seeks to develop beyond Spacewires project (Jiang et al. 2014) also uses a banding like dimensional printing based on structural performance (Yuan et al. strictly layer-based methods that build up in 2D planes in the technique but the shape of these bands begin to take influence 2016). Other structurally focused research has been undergone z-direction. While all freeform printing precedents incorporate from the overall form of the object rather than being cut through non-freeform, but spatially deposited material that varies simultaneous x, y and z axes movements, many still build an XY plane. Their project is heavily focused on computational due to being locally based and is on stress lines, as shown in geometries using a ground-up system. As touched on previously, complexity, and this more complex and variable 'slicing' or Figure 12. areas and layered up vertically (as seen in Figure 1). Projects qualities. Curvoxels, (Hyunchul et al. 2014-2015) researched the By taking into consideration the influential factors from the such as those by Mueller et al. (2014), Ai Build (2016) Branch use of 'spatial voxels' as a tactic for breaking up geometries performative and materiality findings of these projects and Technology (n.d.) & Gramazio Kohler Research (2015 & 2012-2016) and printing them in voxel structures that build up like blocks. combining them with the structural successes of the output use a very distinct banding approach as their process towards While this is again using planar slicing techniques and building focused projects, there is potential to create processes that breaking up large geometries into layers of spatially printable ground up, the structures inside the voxels are varied in density maximise the opportunities that arise when designing a toolpath bands. The benefit of this is, as in traditionally 3D printing, almost and geometries to reflect the local structural needs of the object, spatially as opposed to through layer based formats. The all geometries can be run through a slicing system, and turned into once more through the development of complex computational structures of Laarmans Dragon Bench begins to visually move the methods as well as structural analysis.

successful prints due to the fact that the geometries are directly experimental research often look at particular aspects of the expands and contracts around form. Reflecting the intentions of comparable to the intended digital models, with little material printing process and exploit or utilise them in various ways. the defined Form Responsive Method (Figure 2). distortion or impact from outside factors such as gravitational force. Projects Hybrid Phantasm (Disney Design Studio et al. 2015), and In reflection of this, these projects are more output based than Autonomous Tectonics (Del Campo et al., n.d.) let the material be As discussed, the approach of many of the freeform precedents experimental as they focus on creating structurally sound objects the driver of the process and form responds to how the material takes inspiration from slicing software like that of common 3D or constructs that reflect a desired form or surface structure with a reacts to outside influences, such as seen in Figure 11. Many of printing toolpath generators in which majority of motions take the more technically, structurally, and efficiency focused research place in the X and Y axis. This research seeks to manoeuvre projects look into how materials and freeform processes can toolpath generation away from trying to be an all-encompassing While the aforementioned projects all use 3D bands that build be utilised to enhance the performative value of the object or printing process that can print any input geometry through a up cumulatively, other projects use a similar approach but start to materials, such as through multi-extrusion tools, such as in the standardised process. It instead looks to utilise diverse tactics let the toolpath and material deposition have more response to projects Freeform 3D printing: Towards a sustainable approach for Designed Deposition as an integrated approach between the geometries at hand or the requirements of the objects. The to additive manufacturing (Oxman et al. 2013) and Robotic Multi-consumer, designer, computer and digital realisation.

process away from layer-based tactics which can result in lowresolution qualities. By allowing form to influence structure with Arguably, the projects using this printing approach have the more The projects that have less focus on output and more on greater intricacy and consideration, (as seen in Figure 13), structure

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

can collide into existing geometries if undercutting forms are project. delineated.

can be customised for bespoke construction processes, simply well-considered toolpath creation and informed print tactics. by changing what tool is integrated onto the robotic arm (Budig, Lim, & Petrovic, 2014, p. 26). With an extruder attachment, a large- As aforementioned, the main benefits of 3-axis machinery scale 3D printer is born.

large ABB arm seen in use in Figure 12. While 6-axis of motion has demanding the development of new technologies also. greater flexibility and control, there may be advantages in looking into and comparing the use of 3 axis CNC devices for freeform. This research intends to find the benefits and compare and accessible than their 6-axis counterpart, therefore requiring less when using computer aided design. training, supervision and technical knowledge. While the software

It has been suggested that CNC technologies have greatly or printing information if using an FDM printer needs customisation narrowed the gap between what is plausible in computer-aided to be suitable for spatial printing, little physical manipulation design (CAD), and what is possible regarding materialisation and or maintenance is required compared to that for integrating an constructional limitations (Hack & Lauer, 2014, p. 46). Through extrusion method to a 6-axis robotic device. Syncing physical additive manufacturing, 3-axis CNC capabilities and extrusion movements of these devices with extrusion rates and information methods are used to create geometrically complex forms most requires substantial technical developments. Most freeform commonly through layering methods. However, in circumstances precedents develop in-house custom extrusion and cooling where layering is not used, 3-axis can be limiting, as the tool head methods specific to the device, materials, and intentions of their

The dexterity of 6-axis machines is utilised surprising scarcely for Most robotic arms have 6-axis of movement resulting in great governing the direction or angle at which material is extruded. dexterity. This exposes the ability to manoeuver around existing Projects by the Joris Laarman lab, as seen in Figure 15, are the geometries and has a higher level of control over toolpaths and most dominant utilisation of this ability. With this, 3-axis and its tool-head orientation. Robotic arms have been widely adopted inability to control extrusion direction seems to be only a minor in architectural research projects that look into new ways of hindrance. The restraints of lessened manoeuverability for fabricating complex structures. It becomes a powerful tool that collision avoidance could be considerably compensated for by

are the inclusivity towards a wider range of users, and more easily accessible equipment. It allows for the use of a standard For these reasons, nearly all of the precedents looked into were FDM printer to become a tool for spatial printing with minimal working with 6-axis robotic arms. The majority were using large modification. With this, it is primarily a revised utilisation of machine ABB or KUKA models, such by Gramazio and Kohler Research, their control that allows for adoption of freefrom processes, rather than

3D printing. 3-axis devices such as regular 3D printers are easily limitations of freeform 3D printing through 3-axis CNC devices, available, and assembly between CNC device and tool-head is already equipped with extrusion capabilities. The process takes not needed as they are already integrated. 3D printers and other influence from the synergy between software, hardware, and form 3-axis CNC devices currently are more physically and financially that has arisen from the use of robotic arms as a tool for realisation

## STRUCTURES, TOOLPATH AND EFFICIENCY

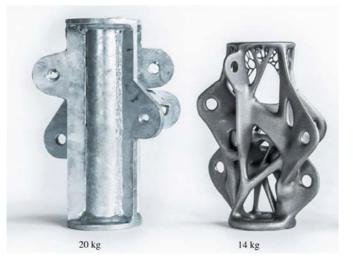


Figure 16. Topology optimisation and reduced waste, photographed by Davidfotografie (Galjaard, Hofman, Perry, Ren, 2015)



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

with project such as Freeform 3D printing: Towards a sustainable needs and parameters for form to 'grow' within. 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-

A range of design research projects pursue efficient use of effective, and mostly wasteful" (2010, p. 80). Galjaard, Hofman, (2015. p. 46) Spatial and custom extrusion methods provide a material. Often inspired by nature they seek to design a process Perry, Rens' Topology optimisation and reduced waste (2015) promising platform to explore this process that Menges and of fabrication, rather than and outcome. The additive process of proved this technique successful in the realm of 3D printing. Kipper propose and prove. The use of self-supporting materials 3D printing finds itself appropriate for this nature inspired stance, (Figure 16). Using Finite Element Analysis (FEA) and defining local diminishes the requirement of a support structure, allowing

> Imitating this growing and adaptive process of biological structure allows for a design and modelling process that Freeform precedents such as Curvoxels (Hyunchul et al. 2014through appropriate material distribution. (p. 36)

rationalisation caused by a separation of design and engineered Variability of material deposition provides an opportunity for control needs, but also begins to provide interesting visual variation. thinking. (Oxman & Oxman, 2010, p. 17). The use of CNC and over the structural implications of its placement. Schumacher et al. robotics has been noted to begin the inversion of this process, (2015) at Disney Research investigated Microstructures to Control While this research is not engineer-based, nor does it focus to material-structure-form. (Oxman & Oxman, 2010; Oxman, N Elasticity in 3D Printing. These investigations provides precedent on structural analysis, it does seek to use material deposition 2010;). This ability allows the designer to engage in the fabrication for AM with variable property design of a single material for not efficiently and effectively in relation to the structural, functional, process from the onset resulting in greater consideration being just variable placement of structural strength, but also tactile and visual and design requirements of objects. Material placement given to material, thus structurally enhanced concepts. According responsive materiality, fabricating deformable objects with spatially will be designed with influence from these research findings and to Oxman & Oxman meaning "There is now momentum for a varying elasticity. Location, direction, and density of material ideas, as opposed to automated slicing or dispersing approaches. revitalised involvement with resources and technologies" (2010, placement can be controlled to create broad opportunities for Spuybroek has discussed the invitation of structured to impress p. 15). Throug inspiration from nature, these projects have come improving material qualities, such as researched by Menges and gualities of aesthetic interest into an artefact and vice-versa, to develop consistent ideals in terms of material deposition, Knippers in Fibrous Tectonics, seen in Figure 17. Their research stating "If ornament can accentuate structural form, structure itself particularly in nature's use of structural necessities as the driver suggests that by orienting and locating each fibre individually in can be seen to contribute to the ornamental." (p.65) of design. Placing material only where needed to perform the space across several layers of hierarchy we can begin to blur the desired functions, compared to our previously subtractive ways boundary between material and structure, and thus "extends the of manufacturing, of which Neri Oxman describes as "much less" scope of design towards the realm of 'designable' materiality."

even more freedom over material placement, therefore creating variable and informed material and structural qualities.

combines structure with geometry, material, function and 2015) and Robotics-Enabled Stress Line AM (Tam et al. 2016) begin manufacturing information to achieve the best performance 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

#### 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







Figure 19. Topolabs Print (Page, 2014)



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

articulates each movement that the printer had made. Through controls the material to a certain level, but also lets its viscosity and physical can emerge.

information to the physical world with greater consideration of use of simultaneous x, y and z-axis movements to enhance the and the New Industrial Revolution (2015).

dimensional informed consideration towards printed textures and effects, visually, structurally and performativity. In this, the centre in Lia's filament sculptures (Figure 18). Lia's series explores using by experimenting with the effects of custom printing parameters systems.

The freeform 3D printing process is transparent and explicit. a 3D printer as an artistic medium beyond layer based restrictions in his Vessel series (n.d, seen in Figure 20). These projects begin Structure, materiality, and process are directly expressed through to create a "series of sculptures are discovered by exploring to blur the linear hierarchy of first defining form and then structure the toolpath that the print head follows, and the outcome visually the parameter space of a base model" (Lia, 2014, para. 6). She and materiality being subsequently considered. this, a conversational relationship between the digital and the 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 In digitally defining each movement, we can translate this and quality, Topolabs (2014) software by James Page brings in the the process of making. This brings a craft-like quality to digitally final material quality and appearance of FDM prints. Printing an Extruded material deposition formed into geometries becomes manufactured objects, reflective of the premise of the work initial support structure in the traditional planar layering method of reminiscent of strands of material fibres being crafted into textile collated by Lucy Johnston in Digital Handmade: Craftsmanship printing, the final print layers are subsequently layed down through fabrics. On these grounds, textiles provide vast inspiration for fully three-dimensional toolpaths. While it's not purely freeform possible materialities, textures and tectonics that could be printing, it shows the advantage of material deposition that is employed to freeform print toolpaths. Many textiles projects In designing the whole process rather than just form, the opportunity three-dimensionally informed by the geometries of its artefact, explore similar concepts to what is of interesting potential arises to encode material, not only with structural or functional seen in Figure 19. Peeters' Drooloop Flowers (2014) is a maker-towards spatially printed designs. For example, Rita Parniczky's material qualities, but also tectonic, visual, and expressive culture example of how simple processes can be undergone to architectural inspired work that looks at explores the performance qualities that inform the product with an expression of its making. create variable printed tectonics that provides visual expression and movement of the vertical monofilament lines (in her X-Ray This allows for textural qualities to be explored with greater or function relative to the intended outcome. This project also Vault Series III, No I)(2016), and projects from French studio intricacy, beyond forms and surfaces, down to a material level. highlights considerations regarding cooling time and toolpath, Matières Ouvertes in their exploration of fibre based structures This provides an opportunity for a broadened and more three- and how these can be exploited or controlled to create varying and variable densities (2013). tactility. The usually unwanted 'low resolution' or stair-stepping structure is printed by using a layered and consistent process for With inspiration from the qualities and knowledge found in aesthetics and tactile trait that comes from print layers can instead a sturdy stem-like structure. 'Petal' sections are printed with the aforementioned research and precedents, there is opportunity be reconsidered and reformatted to become a design element. fan off and with custom settings to result in more naturally formed to discover how material deposition can be further crafted and This greater homogeneity between the digital information and and tectonically considered materiality. David Lobster is another encoded with structure, tactility, visual interest and materiality with physical realisation means we can craft digital technology, such as artist using custom FDM processes to create unique materialities greater consideration than that possible of current banal layering

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)

1.1

## 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

(Angioni, Cabiddu, & Di Guardo, 2012).

In 2003, Bak recognised that the application of additive tectonics to be of benefit to the end-use of a product. manufacturing is inherently linked with rapid prototyping, and

3D printing and CNC technologies allow the possibility to machinery needs to become less expensive to buy, maintain, and Spatial printing processes allow some of these values improved industrially manufacture individual non-standardised elements use, as well as being developed to support the creation of end further, such as in the vast reduction of waste material, therefore (Gramazio, Kohler, & Oesterle, 2010). With these technologies product fabrication, rather than at prototypical quality. (Wohlers, requiring less post-print clean-up. Although still in its early research there is no incentive or benefit in manufacturing duplicate objects 2003, as cited by Bak, 2003, p. 340) This development towards stages, with development there may be potential for a unique as there is when tooling and moulding are involved, thus, it end-use or end product fabrication is emerging, with technologies path towards end-use additively manufactured products through becomes appropriate for consumer customisation services. This for Additive manufacturing methods increasing in complexity, freeform 3D printing methods, enhanced through the integration has been implemented by (Rosenkrantz & Louis-Rosenberg, accuracy and many other aspects. Further growth is foreseen, as of mass customisation and rapid production. n.d.) through generative modelling and an online customisation identified in a report published in Stratasys Direct Manufacturing service. Beyond AM, mass customisation has been implemented Trend Forecast (2015), with note that this "expanded adoption of New platforms are being developed to help accommodate this with proven success, most notably by Nike, through their service 3D printing for end-use parts does not happen in the blink of an notion. MatterMachine (n.d) is an online node-based parametric Nike Id (n.d.). In fact, Nike Id was originally only meant to be a eye—it happens one application at a time" (p. 25). In mass, it seems modelling programme, seeking to play part in the democratisation marketing campaign, but its user input tapped into the interest that realisation towards this goal will be found through high- of manufacturing. The programme is made for ease of both of the consumer and "through the exploitation of technological" resolution parts, with minimal visibility of print lines. Freeform 3D designer and consumer with platform for easy adjustment of developments, rapidly became a major strategic asset to Nike" printing could offer a new path in searching of this end-use goal. inputs, and output of manufacturing data. Programmes such as this In celebrating the manufacturing process, material deposition and show value in how generative platforms can begin to integrate toolpath, we can exploit the spatial method and exposed printed mass customisation and rapid production motives that include the

anticipated a merge of these capabilities with the high-volume Rapid production of additively manufacture objects in terms of Grasshopper is well established with vast resources and plugins production of conventional manufacturing (p. 340). This was production economics encompass several cost advantages; lesser to aid the creation of complex models and information. For these described as rapid manufacturing, refering to the delivery of waste than subtractive processes, input material is consistent, reasons, Grasshopper is used as the parametric platform for this finished goods directly from digital data, leading to tool-less meaning no inventory of a variety of standard-sized stock is project, but the web-based structures provide promising platforms production and the mass-production of individually customised necessary, reduced labour for fabrication and assembly, and better for bringing mass customisation methods to be realised in future. goods. It is advocated that for rapid manufacturing to infiltrate new quality control as production is digitally driven thus less room for markets more effectively, some changes need to occur. Namely, human error as well as minimal setup costs (Bak, 2003, p. 341).

consumer as part of the design process.

#### OVERVIEW AND INTENTIONS

possibilities and applications for spatial printing methods. Through respect and response to the needs of the product, its user and the use of 6-axis robotic arms, the process has been exemplified the manufacturing method, opportunity is exposed to embrace a for the creation of complex architectural geometries with real revitalised relationship between the designer and the digital. New world application. Experimental freeform projects and the maker methods will be developed and explored with the intention of community have started to digress beyond traditional layer creating objects for applications beyond prototypical use, working based printing techniques and begun to experiment with how towards product based outputs. more variability in settings and material deposition can be used to enrich visual and tectonic qualities. Structural and technical Exploration of user customisation will be integrated through pursuits express value towards more informed and economic the use of parametric modelling. The research seeks to find dispersion of material.

begin to understand the value of this technique in the spaces factors are actualised. between the micro and macro, the tinker and the engineer. An industrial design perspective provides a new set of guidelines Standard FDM printers will be adapted as tools for this project. structurally informed freeform printing.

growth. This research however, seeks to use freeform printing industrial design perspective. 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.

A multitude of precedents are discovering impressive qualities, By refreshing the way we approach digital technologies, with

techniques that allow material dispersion to respond to elements of form, aesthetics, structure and function, as well as how users By amalgamating these concepts and successes, one could could be providing input and controlling parameters of how these

and proprieties to interpret the process through. This provides This use of 3-axis machinery will be explored in comparison to a context to develop artefacts with curated materialities for the large body of research completed through 6-axis robotic the integration of output focused, tectonically considered and 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 Traditional slicers of AM and the material dispersion systems seen on this inclusive and concurrent conversation between designer, in many freeform precedents hold value in their ability to take user, and technology, it aims to prosper upon expedient print almost any 3D geometry and make it printable through upward factors to discover new opportunities for materiality from an

> 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

## METHODOLOGY / DESIGN PROCESS / AIMS AND OBJECTIVES

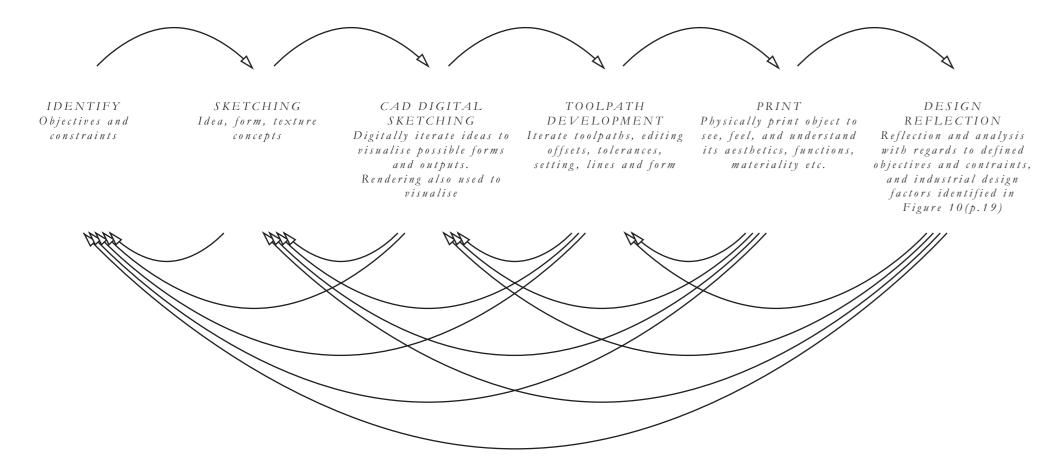


Figure 21. Author, Iterative Design Process

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

approaches related to spatial AM and material deposition, research were discovered, explored, analysed and discussed Subsequently, this information is structured and organised into & Hanington (2012) and Cresswell (2013), developed necessary subject discussions. comprehension of the existing state of the field and aiding the discovery of possible opportunities within the scope of the Aim 2: To investigate, explore and exemplify design both static and parametric, will be used to develop forms and research. The realm of this spatial AM technique is relatively potentials of spatial printing techniques with recent in its advent, leaving many technical aspects still in informed material deposition from an industrial development. Artefact analysis such as described by Martin and design perspective. Hanington (2003, p.14) is an opportunity to systematically examine the material, aesthetic and interactive qualities to help understand It is presented by Godin and Zahedi (2014) that there are three are used to get the overall design form and idea developed to many implications (p.24-27).

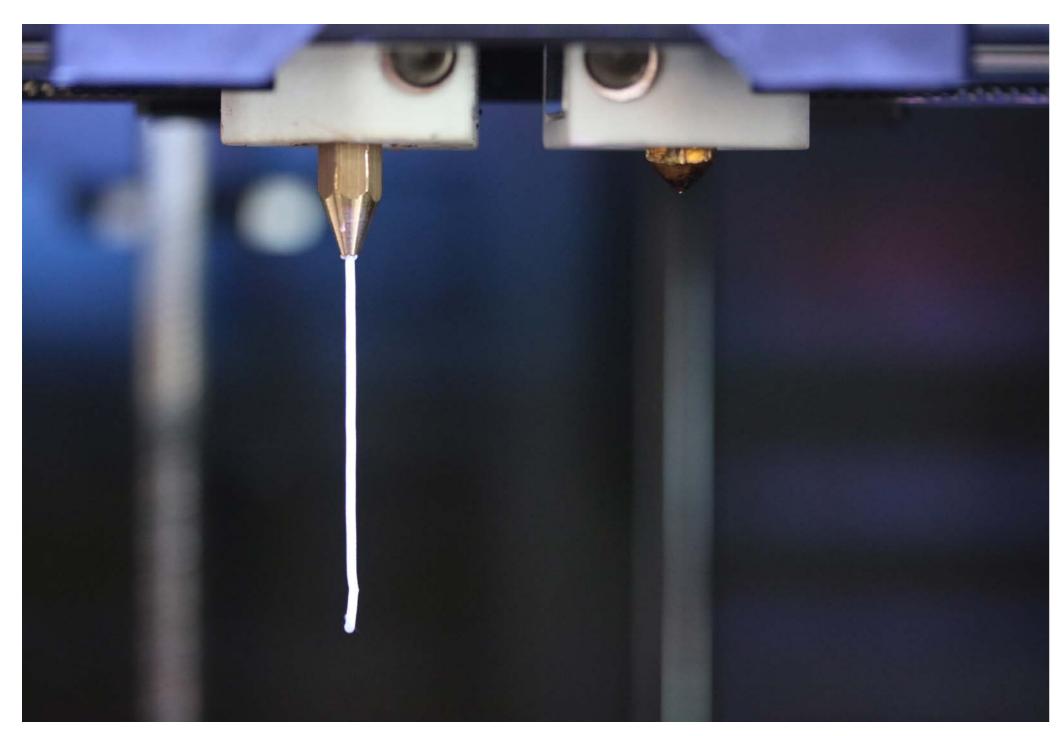
recycling using precedent-based analysis and synthesis models. process is pursued. Preliminary tests to define appropriate print Eilouti's emphasis is on recycling and building upon existing settings and physical necessities are undergone with relationship knowledge to inform future works. This process begins with raw to technical and material information. These digitally defined and data being extracted from precedents' documentation, achieved pre-extrusion aspects are then to be tested in terms of deposition With the objective to identify current technical and theoretical by undertaking thorough background research matrix (Figure 3, in abstract experiments, in order to discover the implications of p.12), as well as supplimentary research that was undertaken. This geometries and the process of laying down materials, with varying exemplary literature and projects that hold relevance to this is then to be reinterpreted and transformed into useful information. unique intentions. to gain a depth of knowledge within this field. This literature developed abstract models of knowledge, discovered in the Represented in Figure 21 is a structure of the design process that and precedent review, informed by such methods from Martin information collated through pages 24-27, and throughout the is utilised for the development artefacts, both experimental and

existing contexts and implications. This premise was integrated main forms of design research; research for design, research into a suitable resolution. Frankel and Racine (2010) suggest that the into the precedent and research matrix (Figure 3), and specific design, and research for design. Due to the iterative, physically most important aspect of research through design is that it seeks technical information was further interpreted that helped inform explorative, and applied intent of the research, a research through to provide an explanation or theory within a broader context. The a greater understanding of how outputs were created and their design methodology is utilised for subsequent work such as those objective of this research is to investigate opportunities towards described by Frankel & Racine, 2010, Martin & Hanington, 2012, informed use of spatial material deposition from an industrial and Milton & Rodgers, 2013. Fankel and Racine suggest that design perspective. Requirements and aspects leading towards As a whole, this matrix was developed in order to understand "in this approach, the emphasis is on the research objective of this criteria were defined in the small analysis in Figure 10 (p.19). and to build platforms of knowledge gained from these projects, creating design knowledge, not the project solution" (2010, p.6). These are to be used as design constraints, to be responded to extracted from a variety of research pursuits. This comes from the Towards this design knowledge, the objective to conduct material during design development and iteration. influence of tactics suggested by Eilouti (2009) in design knowledge and form experiments and determine strengths and limits of the

application-based. The CAD/CAM realm is where the process finds itself heavily situated. Various computational strategies, 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



PART 2



## 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.

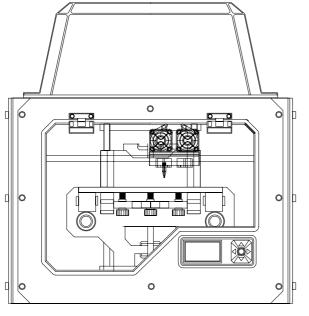
- Creating custom computational processes that create G-code from an input curve/toolpath.

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

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Figure 22. Author, Makerbot Extruder Head

## 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

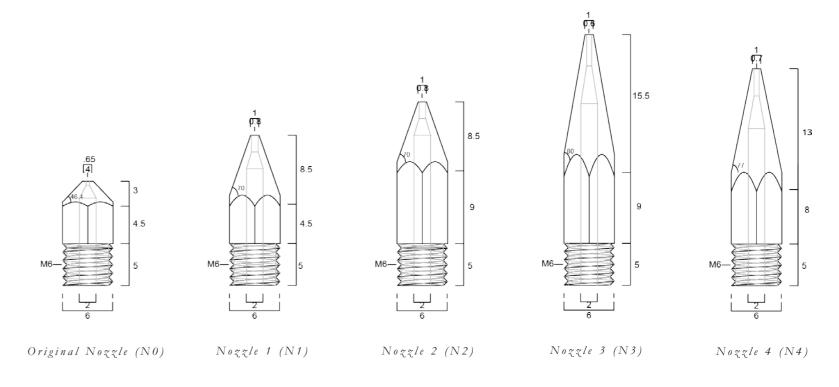


Figure 24. Author, Nozzles 0-4

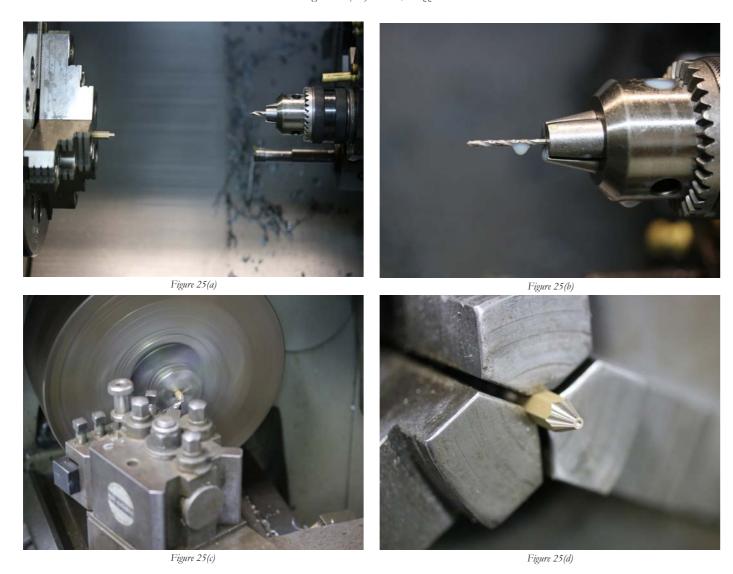
A range of new nozzles was developed specifically for spatial printing. The Original Nozzles' (NO) extrusion diameter and overall dimensions are small, as optimised for standard layer based FDM printing. Freeform printing called for adjustments in these dimensions, thus new nozzle iterations were developed 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



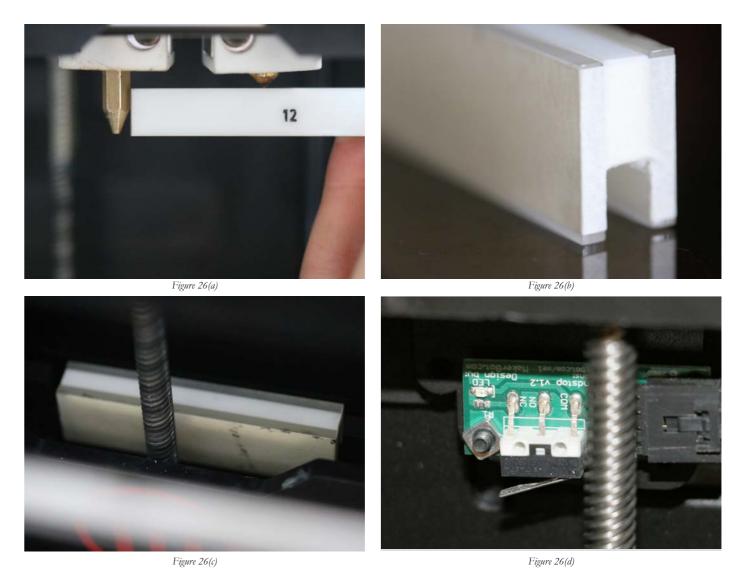
CNC Haas Lathe for creation for M6 thread and 2mm hole for 1.75mm filament to run through seen in Figure 25(a) and 23(b)

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

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## PRINT BED OFFSET FOR NEW NOZZLES

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



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

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-I).

#### 1. Remove filament

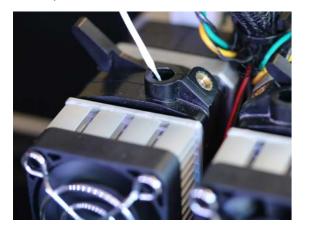


Figure 27(a)

## 7. Unscrew connection from extrusion brace

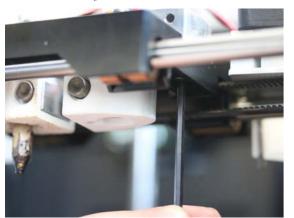


Figure 27(g)

#### 2. Release both screws from Fan



Figure 27(b)

## 8. Remove brace for access to nozzles

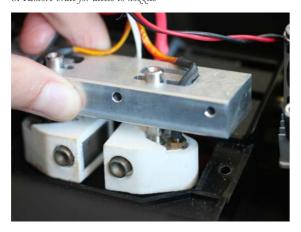


Figure 27(h)

#### 3. Remove fan assembly

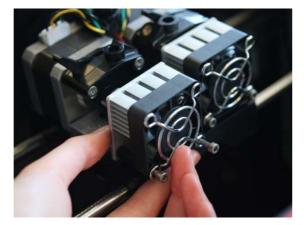


Figure 27(c)

Figure 27(i)

## 9. Release screw holding the heater



## 4. Unplug wire connection







Figure 27(j)

#### 5. Remove extrusion assembly

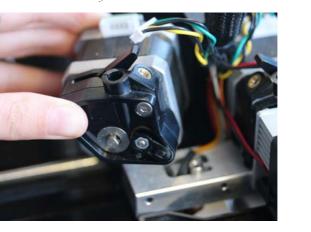


Figure 27(e)

## 11. Place strong object in heater cavity for resistance. Uunscrew nozzle



Figure 27(k)

## 6. Repeat other side so the metal brace is exposed

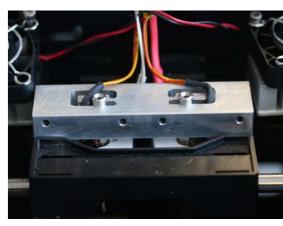


Figure 27(f)

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

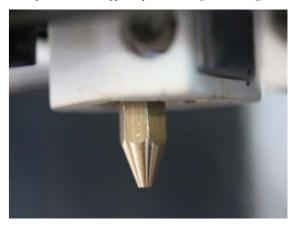


Figure 27(l)

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#### COMPUTATIONAL AND SOFTWARE DEVELOPMENT

or printing information generator. "In fact, more than 90% of based printing processes, the main commands in the G-codes experts agree that 3D printing software has the greatest impact body are the following; 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.

A largely important part of any 3D printing process is the software Silkworm outputs the G-code needed for printing. For extrusion

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

-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/

-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







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



Then run through a converter to be readable to a Makerbot (.x39 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.

# Cull first Item Toggle VARY F VALUE BY LINE ANGLE Makerbot VARY F VALUE BY LINE ANGLE PARAMETERS Move Start point to Zero (for Z) Move center to Zero Generate G-Code VARY F VALUE BY LINE LENGTH Cull first Item Toggle

Figure 29. Author, Grasshopper Script Iteration 1

## COMPUTATIONAL AND SOFTWARE DEVELOPMENT

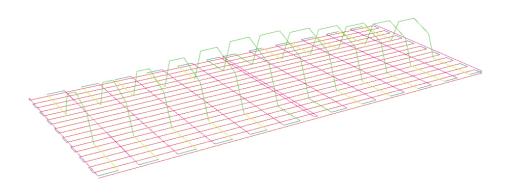


Figure 30. Author, Toolpath Colour Key

Figure 29 shows the first script developed for creating G-code. on. This premise could be used for angles, either angle from the Through a self-taught process, this grew as knowledge of the base plane, or from the last curve, or depending on whether the Z programmes and printing process increased.

The settings and relationships between line length, line angle, Parameters and what was defining the key codes were adjusted extrusion rate, feed rate and temperature were unbeknownst at depending on the requirements of the test print at hand. and 'find and replace' within Notepad++ was used to manually extrusion rates. change these with various settings to test. These could be defined by factors such as line lengths, ie. line lengths within a This script was developed with the intention to streamline once certain range would be replaced with one key (colour or number) the appropriate settings and relationships had been defined. and line length within another range replaced with another and so

value increased or not.

this stage. Thus, parameters and options were set within the script Figure 30 shows an example of the preview of how lines were as to how the G-code was generated and how relationships were separated, in this example by length. Each colour would have a defined. Codes or keys were put in place of the F and E rates unmber key that would be replaced with the desired speeds and

## 2.1

## SETTINGS TESTS - NOZZLE 1 (N1)

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

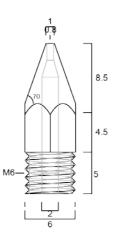
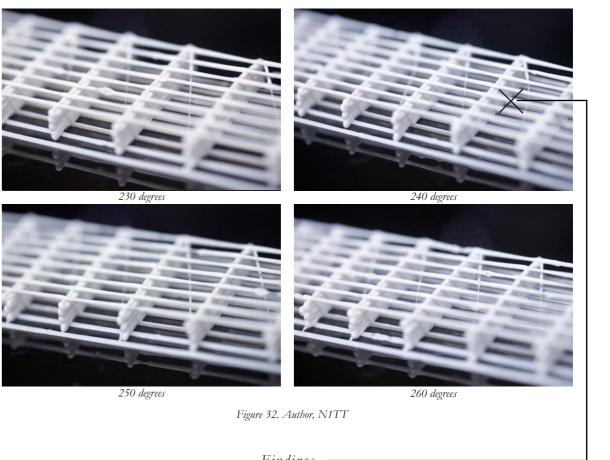


Figure 31. Author, N1 Dimensions

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.



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.

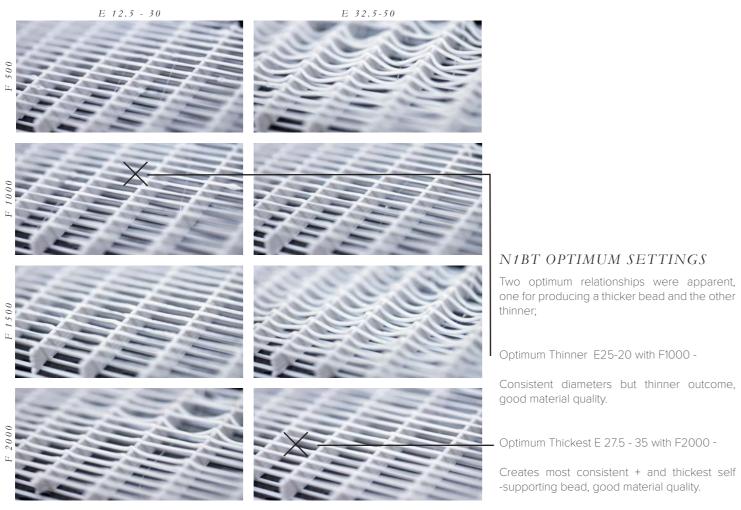
#### 2.1

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## 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



N1BT OPTIMUM SETTINGS

Two optimum relationships were apparent,

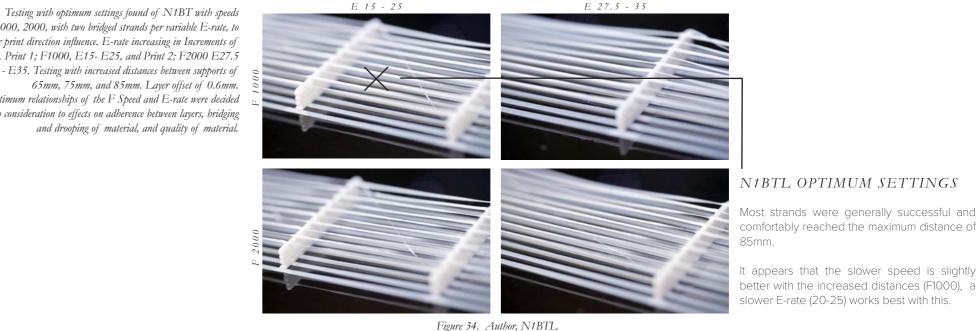
one for producing a thicker bead and the other

Creates most consistent + and thickest self

-supporting bead, good material quality.

Figure 33. Author, N1BT

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.



NOZZLE 1 BRIDGE TESTS -

LONGER BRIDGING DISTANCE (N1BTL)

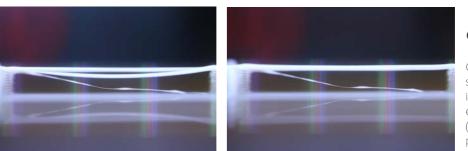


Figure 35. Author, Filament Droop

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.

slower E-rate (20-25) works best with this.

## 2.1

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## SETTINGS TESTS - NOZZLE 2 (N2)

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

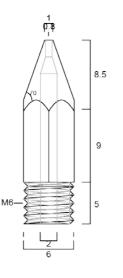


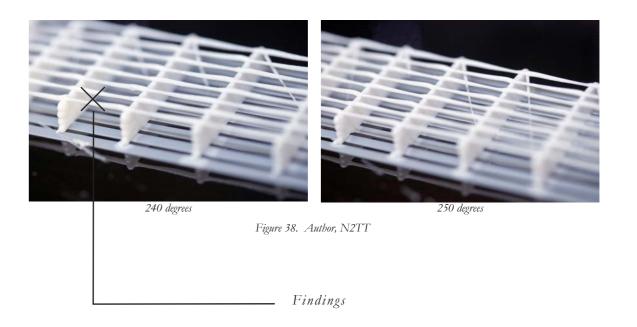
Figure 37. Author, N2 Dimensions

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.



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 -LONGER BRIDGING DISTANCE (N2BTL)

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 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.

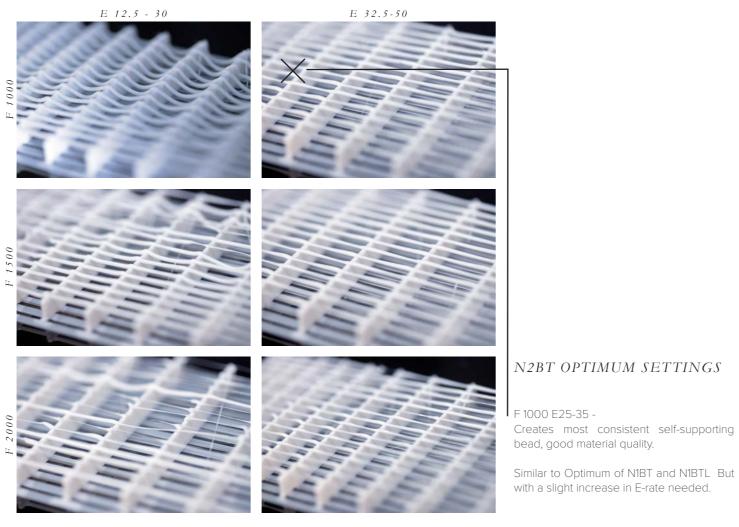


Figure 39. Author, N2BT

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.

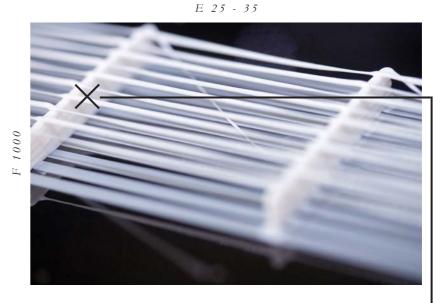




Figure 40. Author, N2BTL

## 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.

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F 1000 E25-35 -

N2BT OPTIMUM SETTINGS

Creates most consistent self-supporting

### 2.1

### 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.

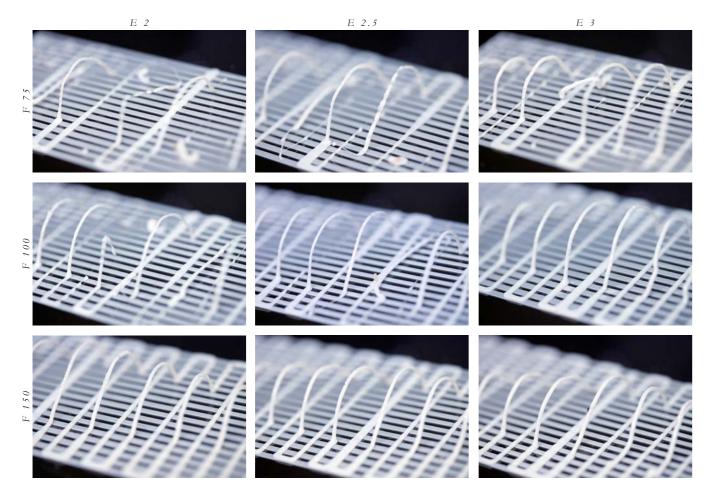


Figure 41. Author, N2AT

### 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			
									E VAUE UP	E VA	LUE DOWN
L		E				Length		*.25	*0.3		*.8
11		3		0.3		7.6		1.9	2.28		1.824
9.5		2.5		0.27		8.3		2.075	2.49		1.992
8		2		0.25		9.14		2.285	2.742		2.1936
	I					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

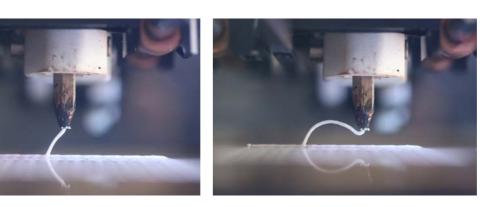


Figure 43. Author, N2AT Up vs Down

### N2AT OPTIMUM SETTINGS

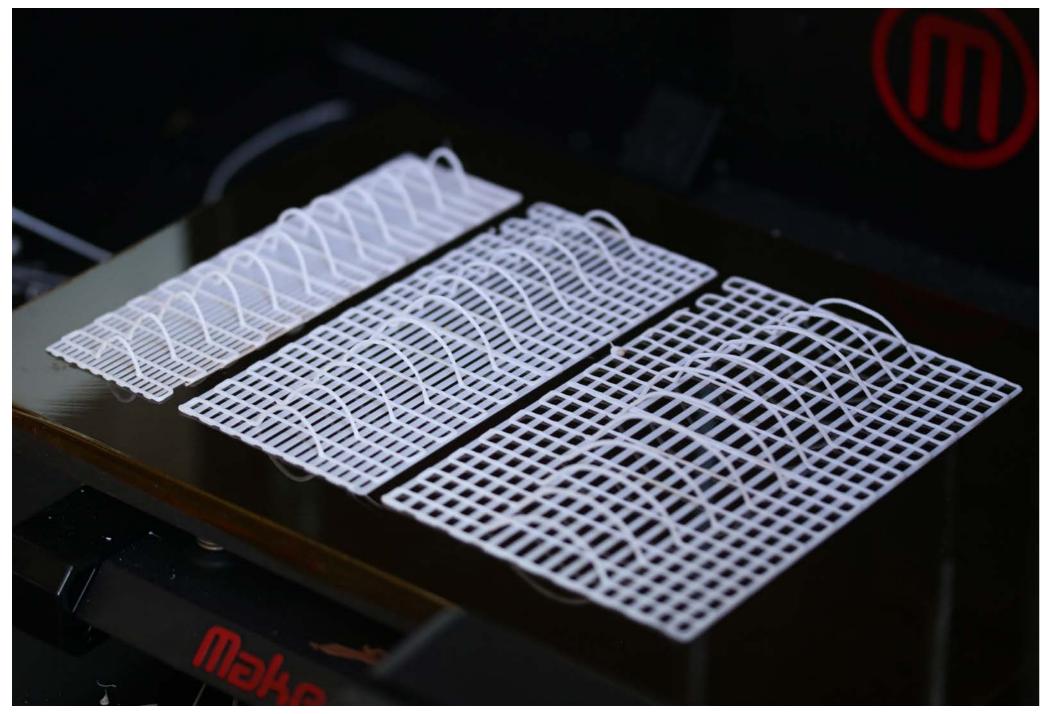
Different E rates and F speed relationships were best for different sized arcs, So in identifying the best-printed arcs of each radius variable and finding the relationship between the setting of this and the correlated lines length(s), the optimum settings could be calculated. The workings of this shown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

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.



### 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

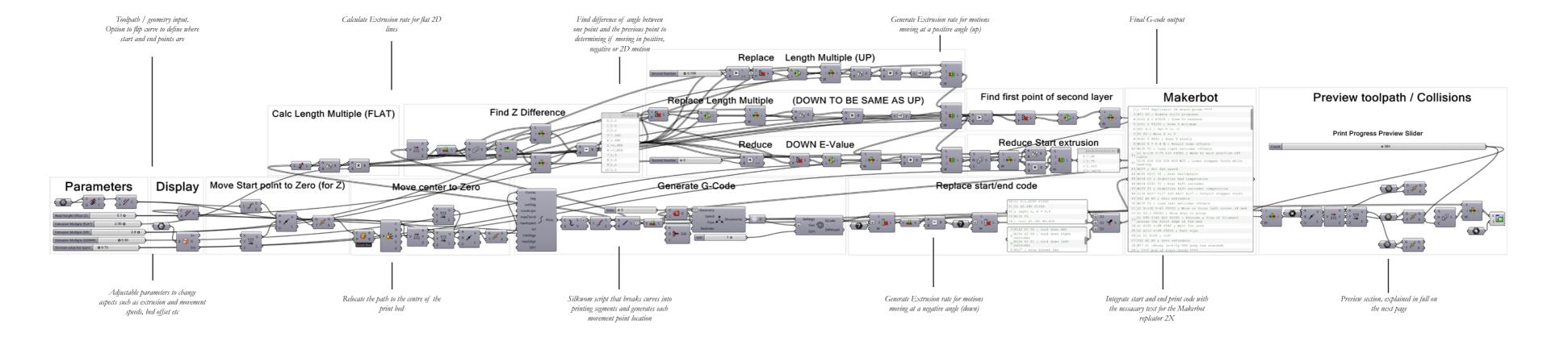
The N2 setting were used to developed an updated grasshopper script.

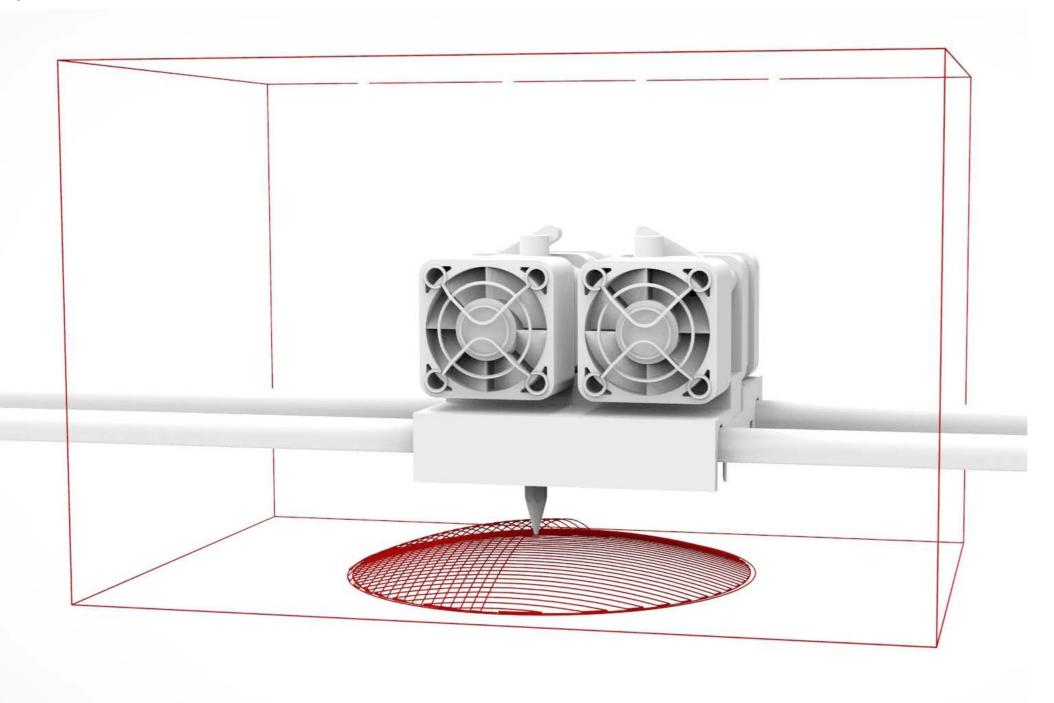
This script was developed and added to throughout the projects.

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 PREVIEW

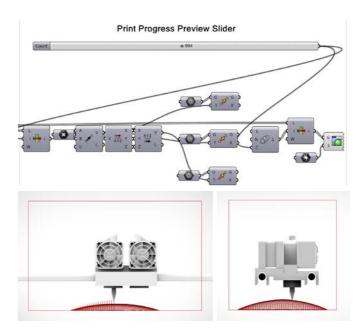


Figure 47. Author, Toolpath Preview 2

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.



### 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

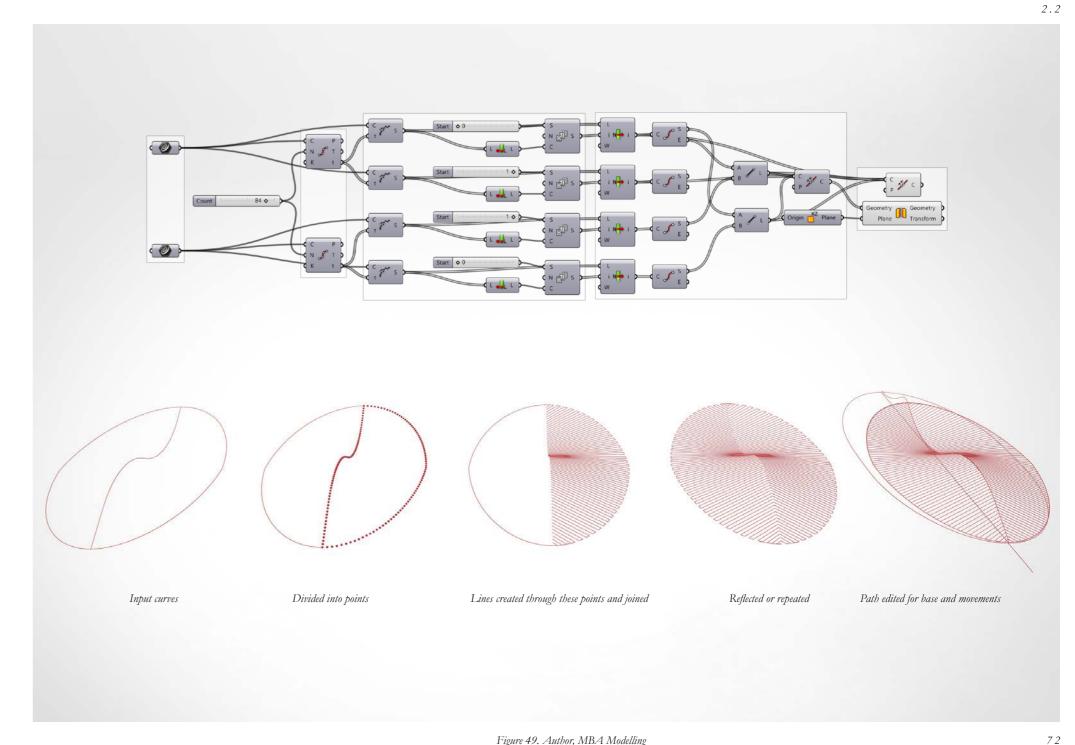
Figure 48. Author, Abstract Design Experiments

### 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.

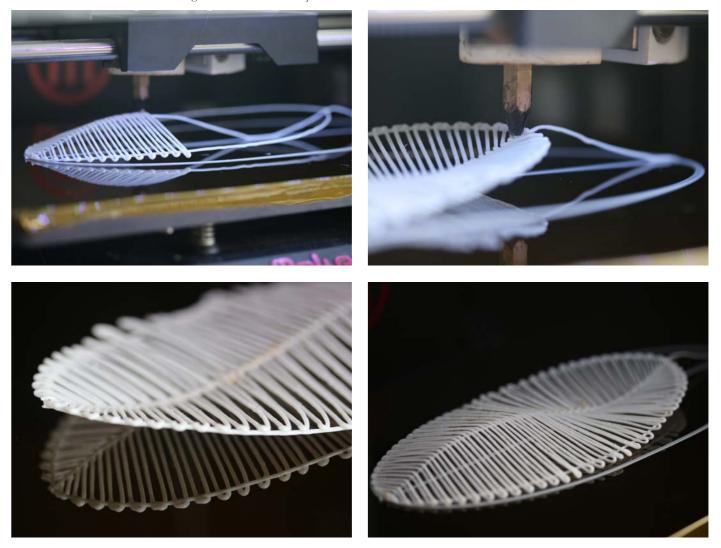


7 1 Figure 49. Author, MBA Modelling

Figure 50. Author, MBA Experiment 1

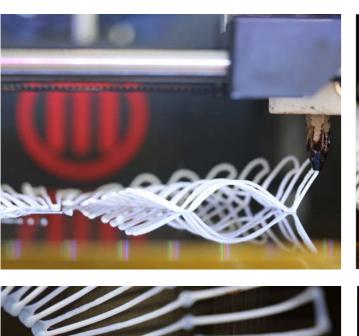
Print Time: 00.41.21 Material Used: 672mm White ABS Nozzle: N2 Settings: N2 settings

Figure 51. Author, MBA Experiment 2

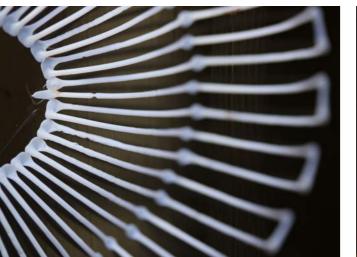


Print Time: 00.54:42 Material Used: 142mm White ABS Nozzle : N2 Settings: N2 settings

Figure 52. Author, MBA Experiment 3



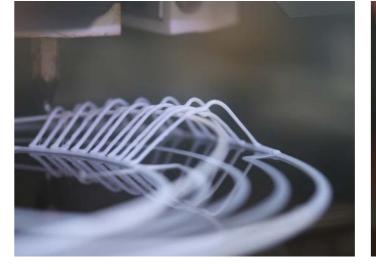






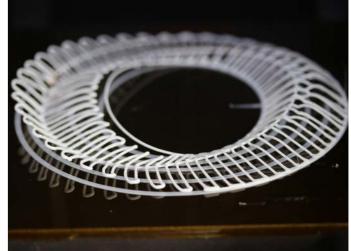
Print Time: 00.46:06 Material Used: 1163mm White ABS Nozzle: N2 Settings: N2 settings

Figure 53. Author, MBA Experiment 4



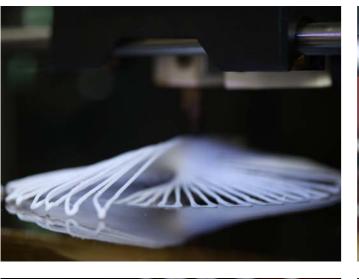


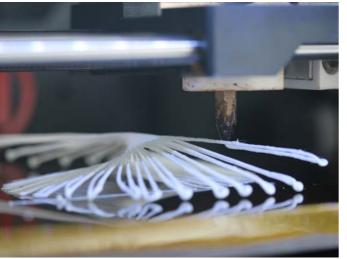




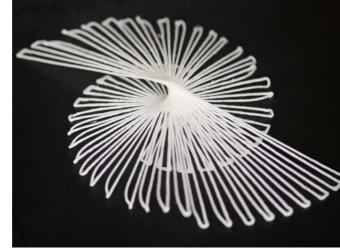
Print Time: 00:44:20 Material Used: 752mm White ABS Nozzle : N2 Settings: N2 settings

Figure 54. Author, MBA Experiment 5



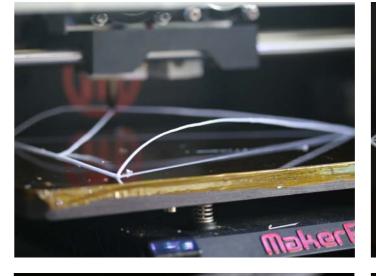


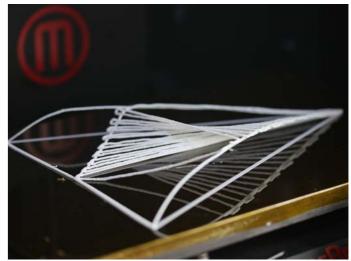




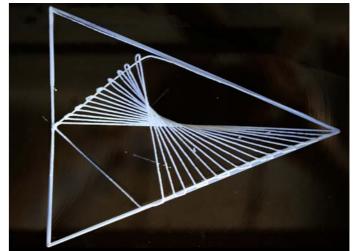
Print Time: 01.11.41 Material Used: 1780mm White ABS Nozzle: N2 Settings: N2 settings

Figure 55. Author, MBA Experiment 6



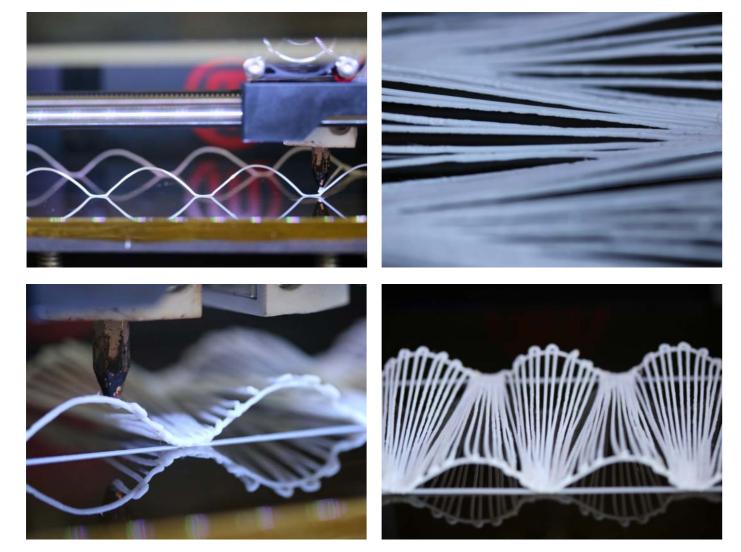






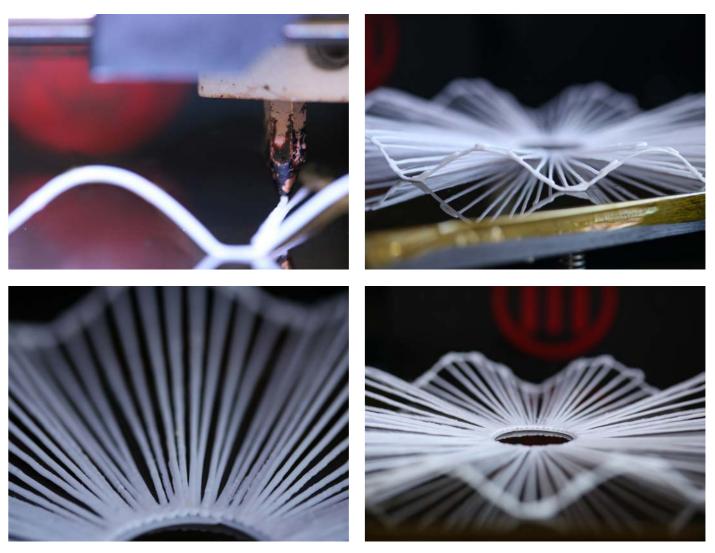
Print Time: 00:32:32 Material Used: 855mm White ABS Nozzle: N2 Settings: N2 settings

Figure 56. Author, MBA Experiment 7



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

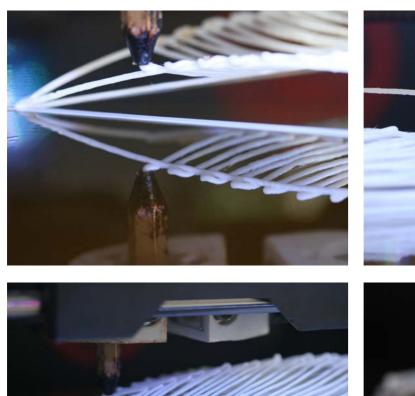
Figure 57. Author, MBA Experiment 8

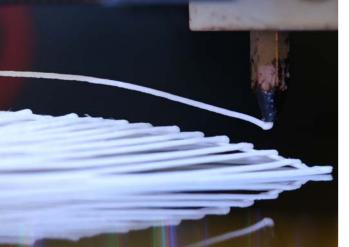


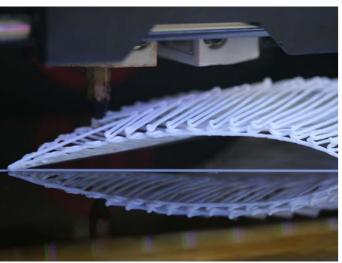
Print Time: 01:15:16 Material Used: 1972mm White ABS Nozzle : N2 Settings: N2 settings

80

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:

### LIMITATIONS:

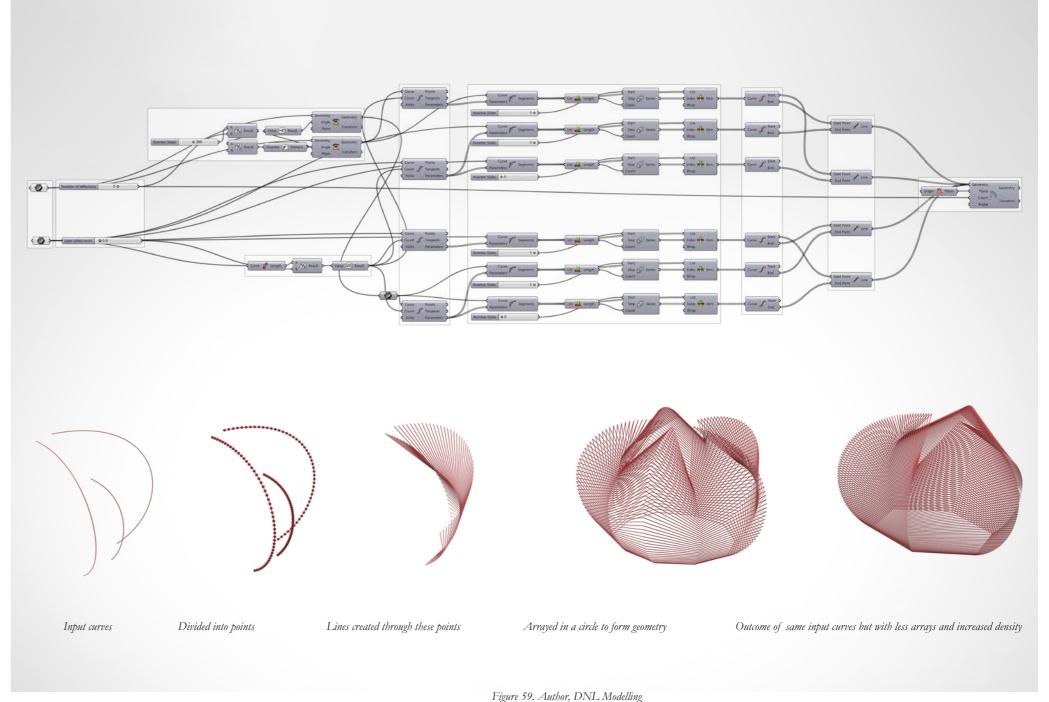
- General ability to dismiss the need to rely to flat base structures to build from, or build up large amounts of support material to do so
- Ability to print largely curvilinear and overhanging geometries
- Ability to widely disregard of rafts or base structures
- Development of modelling techniques without aid of surfaces or solids
- Ability to print some undercutting forms without use of layerbased systems
- Minimal material use and print motions for relatively complex forms

- General ability to dismiss the need to rely to flat base structures 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.

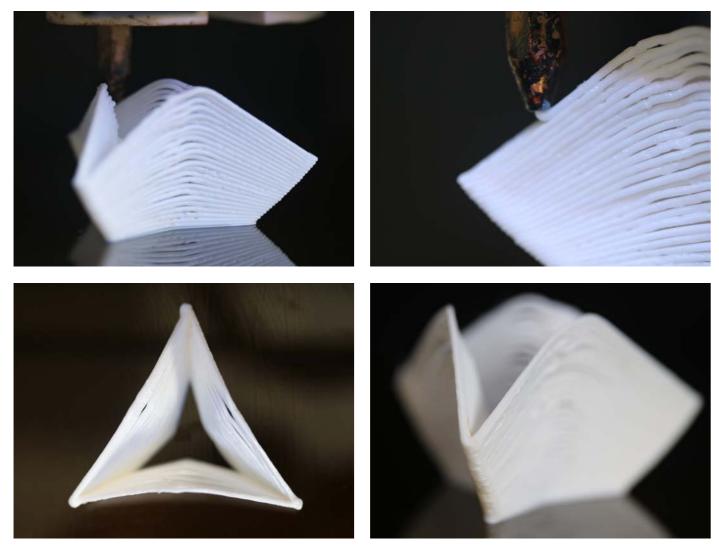
Figure 59 expresses the main Grasshopper script used to create the DNL series models. Based off simple curves and rotational copies (called polar arrays), the fairly simple script allows for seemingly complex geometries to explore dynamic layering techniques through.



1 gmv >>. 1 Innivity D1 (II II) the ming

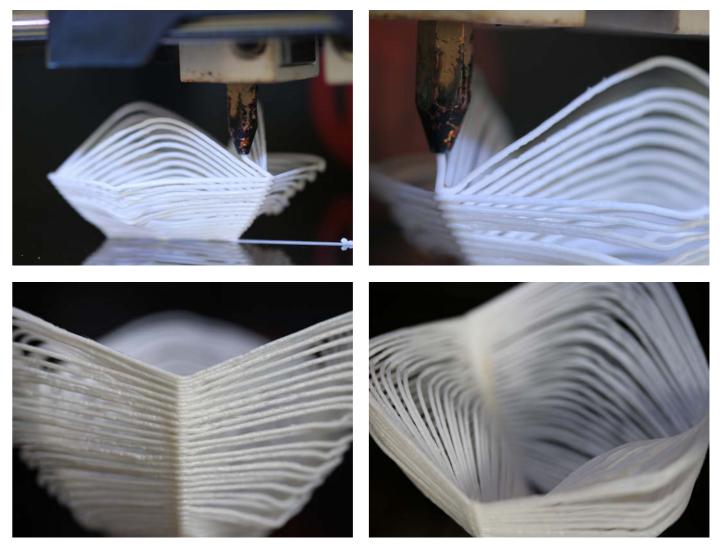
2.2

Figure 60. Author, DNL Experiment 1



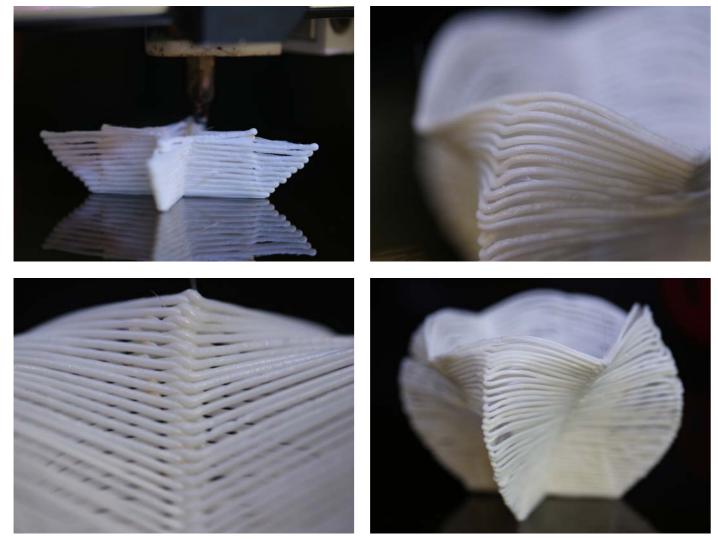
Print Time: 01:24:08 Material Used: 1242mm White ABS Nozzle: N2 Settings: N2 settings

Figure 61. Author, DNL Experiment 2



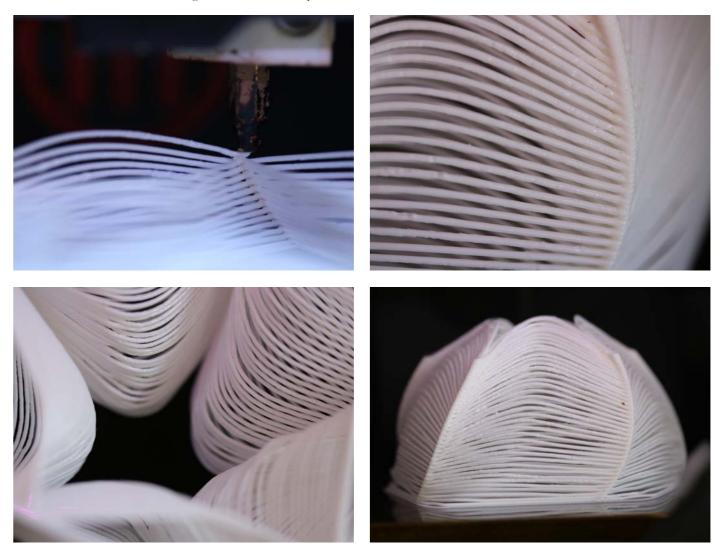
Print Time: 02:08:51 Material Used: 2105mm White ABS Nozzle : N2 Settings: N2 settings

Figure 62. Author, DNL Experiment 3



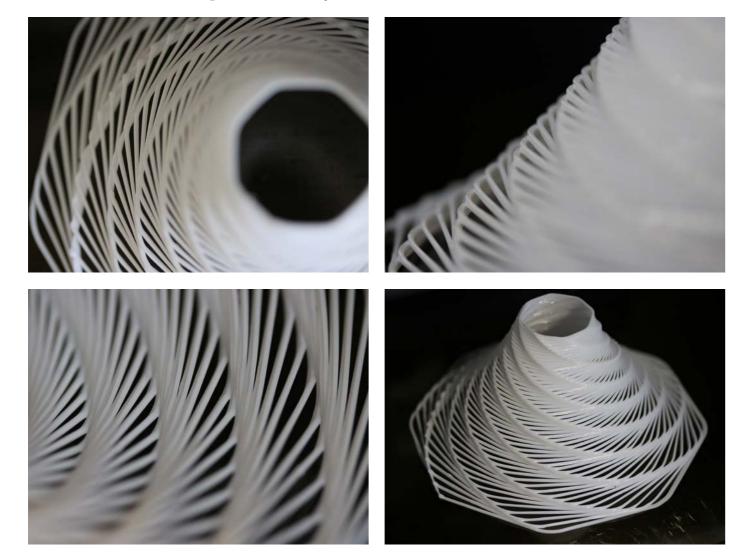
Print Time: 02.15.22 Material Used: 2203mm White ABS Nozzle: N2 Settings: N2 settings

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:

### LIMITATIONS:

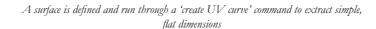
- Broader possibilities of layering when considered spatially
- Sense of reliability regained though building solely ground-up
- Contrast between highly spatial and dense layered areas creates interesting visual and structural qualities
  - Dense areas gain structural integrity
  - Open layers often 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)

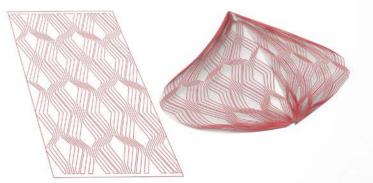
- More delicate tolerances. If any defined point of contact was not fulfilled the rest of the print became compromised
- Being strictly an accumulative process, portions of the prints were restricted by the needed offset from the previous layer, so a defined point needed to reach to build from, causing 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.







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



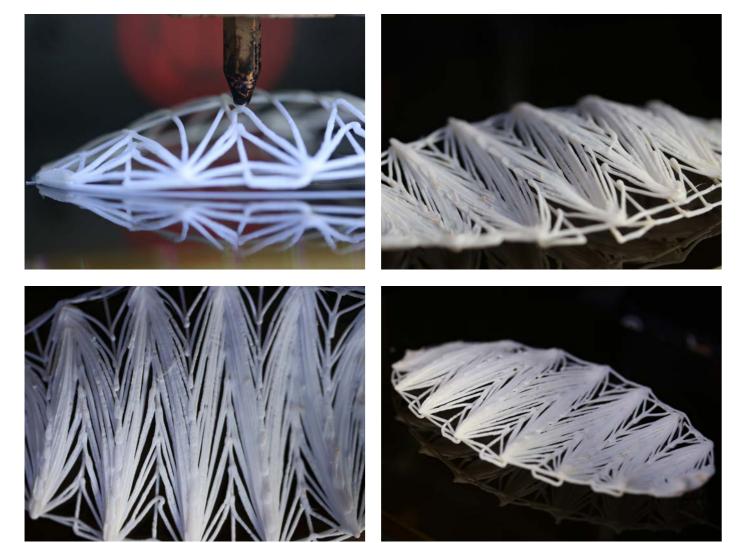
Curves are edited to include any extra motions or needed extrusions.

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91 Figure 65. SPT Modelling

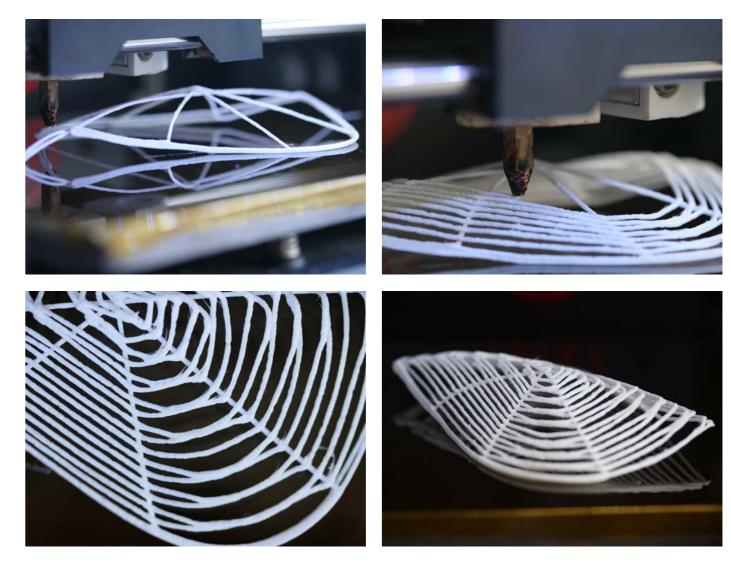
2.2

Figure 66. Author, SPT Experiment 1



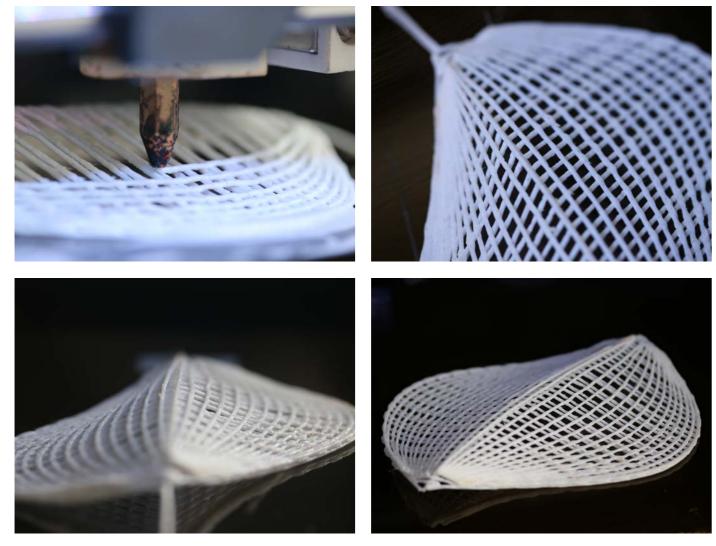
Print Time: 02.01:21 Material Used: 3101mm White ABS Nozzle: N2 Settings: N2 settings

Figure 67. SPT Experiment 2



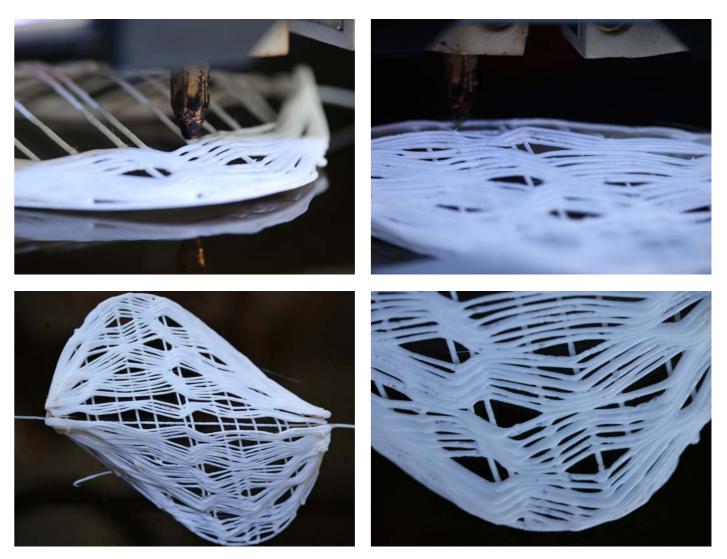
Print Time: 00.43:08 Material Used:702mm White ABS Nozzle : N2 Settings: N2 settings

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



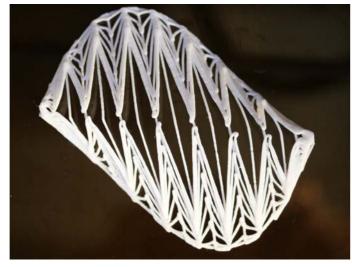
Print Time: 01:55:20 Material Used: 1880mm White ABS Nozzle : N2 Settings: N2 settings

Figure 70. Author, SPT Experiment 3









Print Time: 01:32:13

Material Used: 1504mm White ABS

Nozzle: N2

Settings: N2 settings

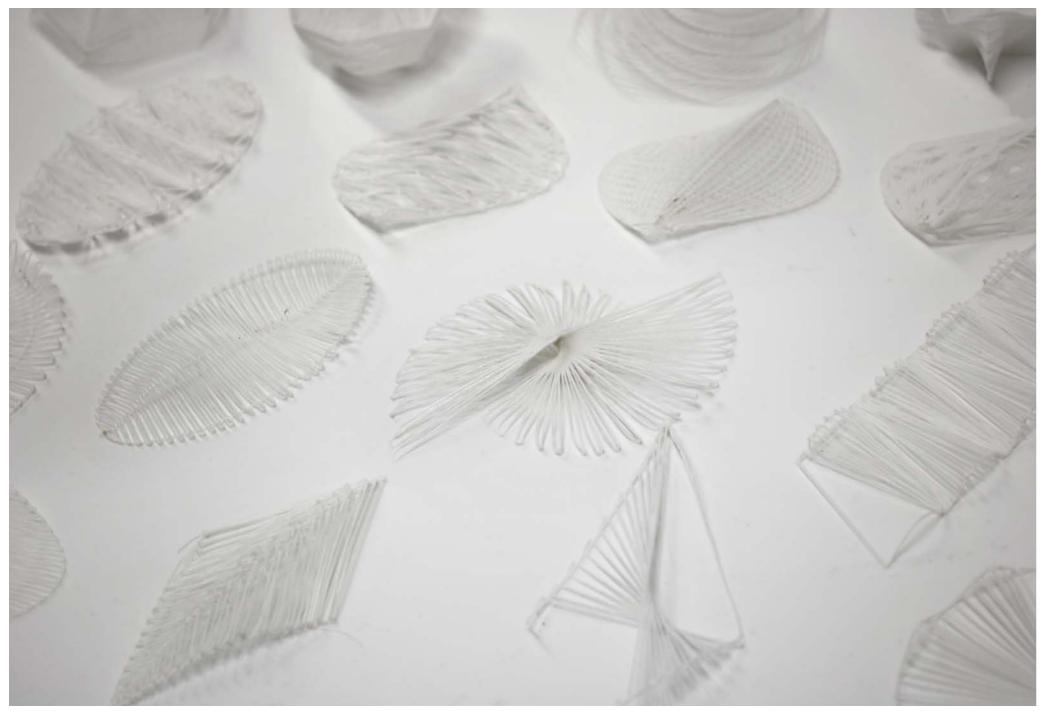
### STRUCTURES, PATTERNS AND TECTONICS - SERIES FINDINGS

### OPPORTUNITIES:

## LIMITATIONS:

- 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

- 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



### ABSTRACT EXPERIMENTS FINDINGS

### OPPORTUNITIES:

processes can create new material qualities through freeform 3D These were primarily; printing. Many specific qualities were found in the experiments, and the integration of these will be used to further increase -Base adherence. While the MBA series proved it possible to opportunity for Designed Deposition. More general opportunities create structures with very little base contact, It becomes very 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 with the extruder and printer components of material
- Greater control over visual, physical and tectonic impact of beginning of the toolpath, to give time for the material to make material deposition
- Ability to efficiently create open or mesh-like structures. (Compared to traditional FDM printing)
- integrity

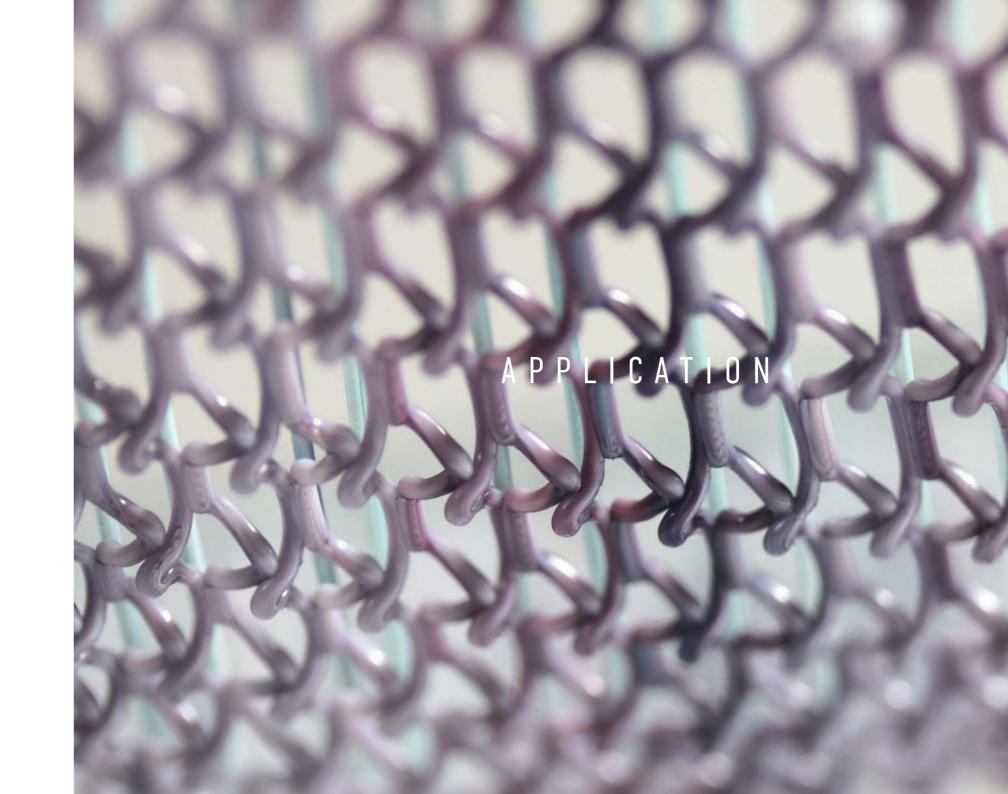
### LIMITATIONS:

These experiments began to express how simple, bespoke A range of limitations or needed considerations became exposed.

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
- Need to start extrusion early, i.e. add an extra length onto the 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 - Visual patterning as a cue for the artefacts use and structural motions and movement between intended geometry becomes a large consideration. These could either be designed into the artefact or be printed and later trimmed

Figure 71. Author, Abstract Design Experiments 100



PART 3



### 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.

103

Figure 72. Author, Machine Adaptation Bits and Peices

### MACHINE ADAPTATION - MENDELMAX

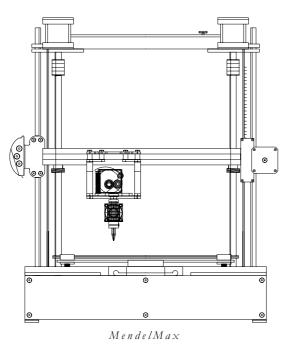
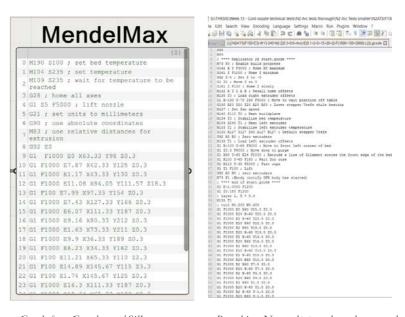


Figure 73. Author, MendalMax Illustration

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.

### 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.

of extrusion tip, and decreased extrusion hole diameter.

Nozzle 3 (N3) - Increased overall dimension, greater angle Nozzle 4 (N4) - Reduced overall body length that N3. Slight adjustments of extrusion angle and extrusion hole diameter.

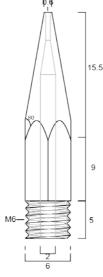


Figure 76. Author, N3 Dimensions

Figure 77. Author, N4 Dimensions

It was found that Nozzle 3's largely increased length was just beyond Nozzle 4 was tested and the settings were adjusted, to eventually find the limitations for successful freeform printing in the manner developed. suitable print settings. These settings were; A large amount of prints with iteration of the settings parameters were created, but no prints were fully successful in their self-supporting abilities. For flat movments; Subsequently, the nozzle was abandoned and a new nozzle iteration (N4) Extrusion rate = Line length x 0.23 created.

Printer speed = F1000

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

These will be referred to as the N4 Settings.



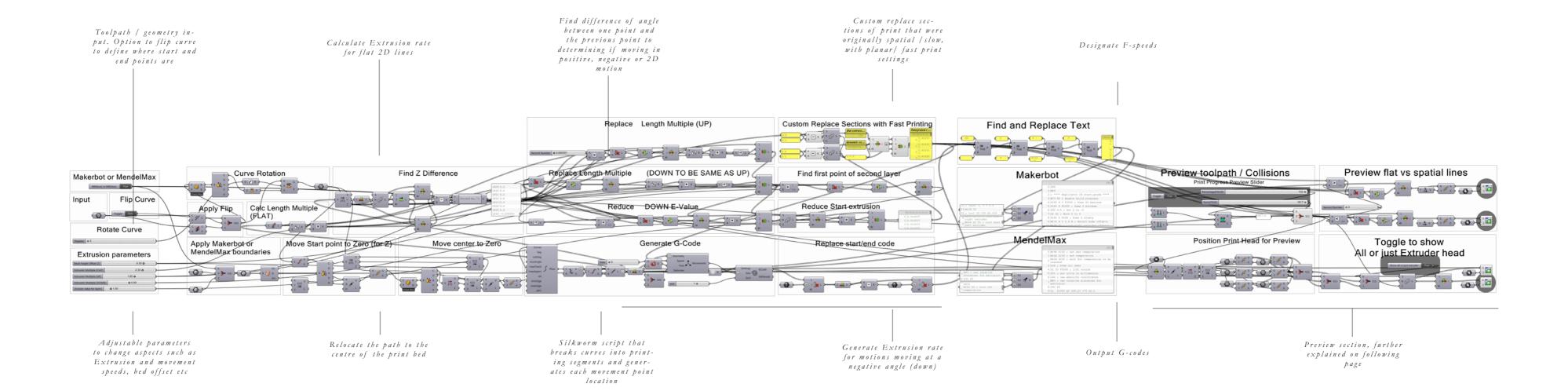
### UPDATED GRASSHOPPER SCRIPT

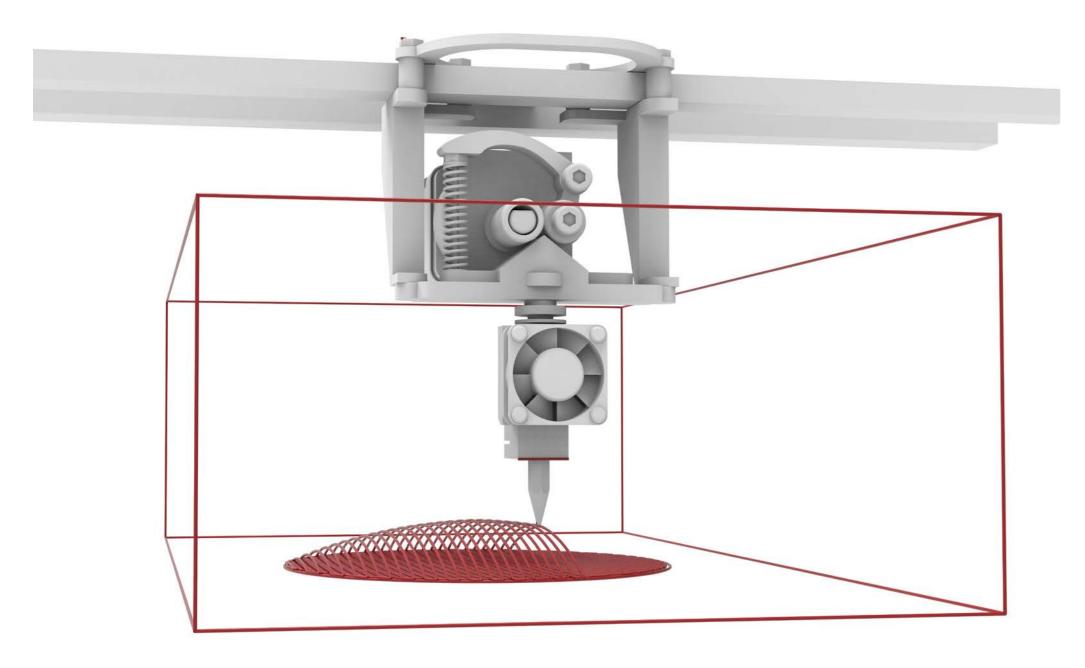
The findings and knowledge gained from the experimentation stage were used to inform further developed the grasshopper script.

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.





### 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.

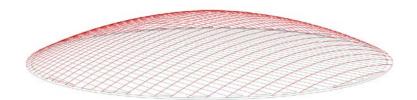


Figure 80. Author, Spatial vs Planar Line Preview

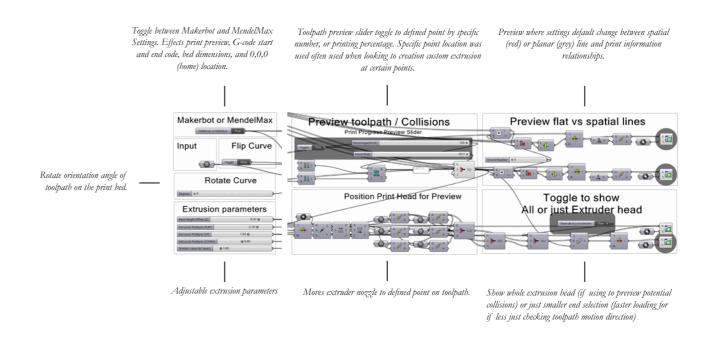


Figure 81. Author, Grasshopper Update Features



### 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.

# Variable Density; Solidity and Open Structure $Exploration; \\ \text{Through Application Experiment 1; a 3 part Kitchen Utensil Set.}$

### 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.

# 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

114 Figure 82. Author, Application Based Experiments

Application 3.2



### 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 83. Author, AE1 Printed Iteration

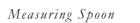
# Digital Sketching Design and Toolpath Iteration Printed Iteration

Figure 84. Author, AE1 Development Process

### KITCHEN UTENSIL SET - DESIGN DEVELOPMENT

Sieve

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







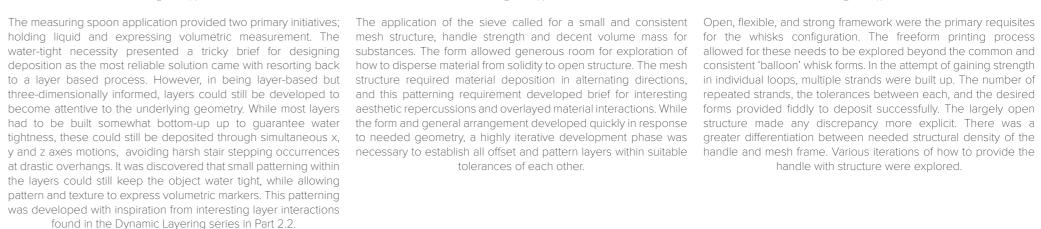




Figure 85(b)

tolerances of each other.



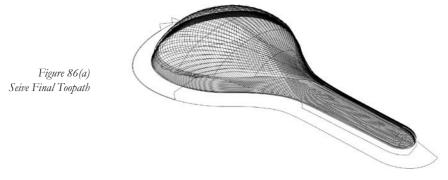
Whisk

Figure 85(c)

handle with structure were explored.

### APPLICATION EXPERIMENT 1; FINAL PRINTS

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



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

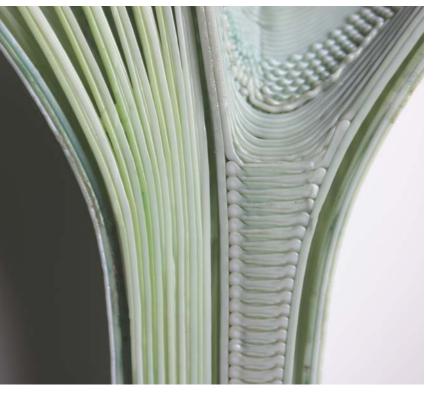
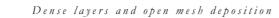


Figure 88. Author, AE1 Final Set

### Directional, structural and tectonic diversity



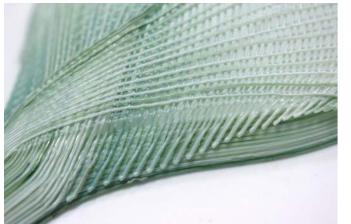
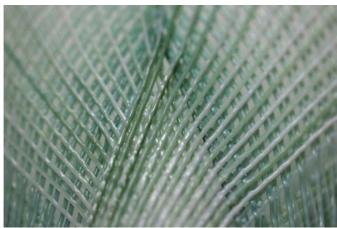


Figure 89. Author, AE1Seive



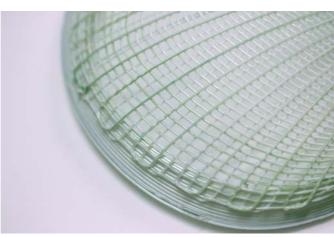


Figure 90. Author, AE1 Sieve Figure 91. Author, AE1 Seive



Figure 92. Author, AE1Seive

### Functional fulfilment - sieving flour

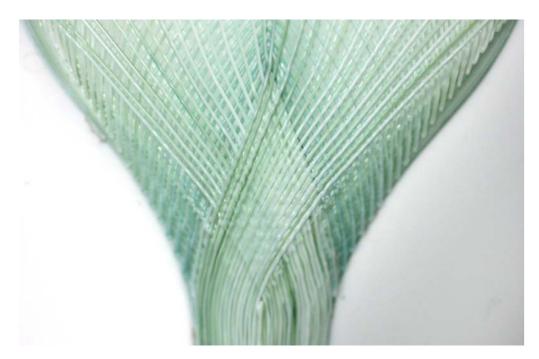


Figure 93. Author, AE1Seive

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



Figure 94. Author, AE1Seive



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 95. Author, AE1Measuring Spoon

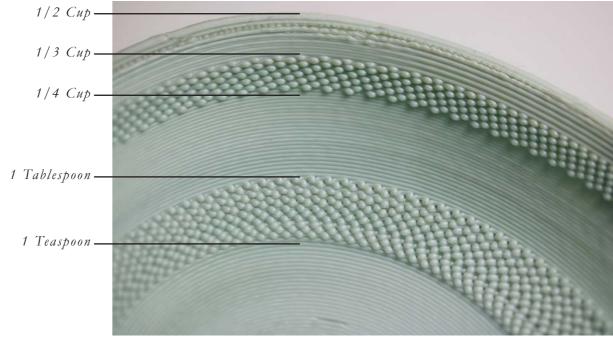


Figure 96. Author, AE1Seive

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

# Figure 98. Author, AE1Seive Figure 97. Author, AE1Seive

Figure 100. Author, AE1Seive

Once measured, substances can be poured smoothly from the spoon

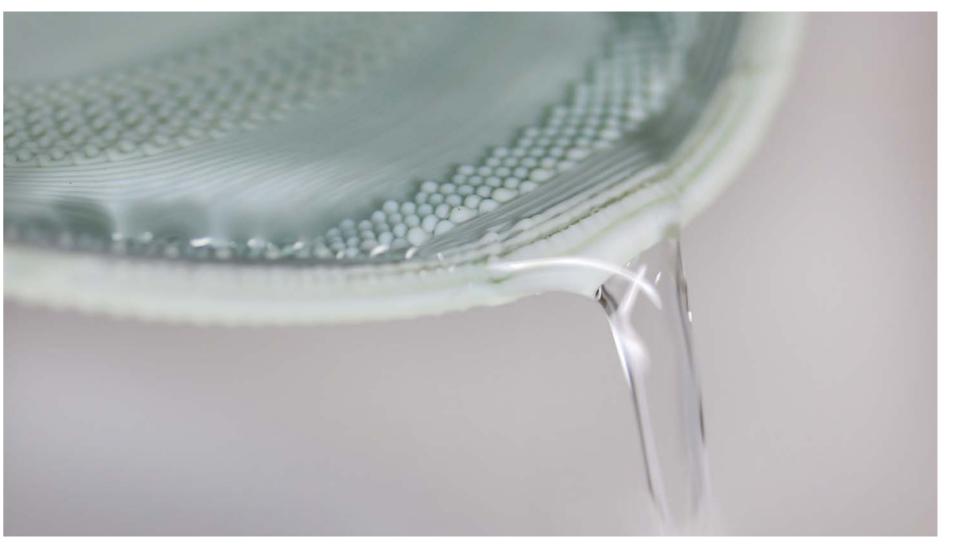


Figure 101. Author, AE1Seive



Opposing directions of material strands improve structural integrity



Denser structure to gain strength in handle



Largely open forms



Figure 103. Author, AE1 Whisk

Figure 104. Author, AE1 Whisk

Figure 105. Author, AE1 Whisk

127 Figure 102. Author, AE1 Whisk



### 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.

1 2 9 Figure 106. Author, AE2 Printed Iteration

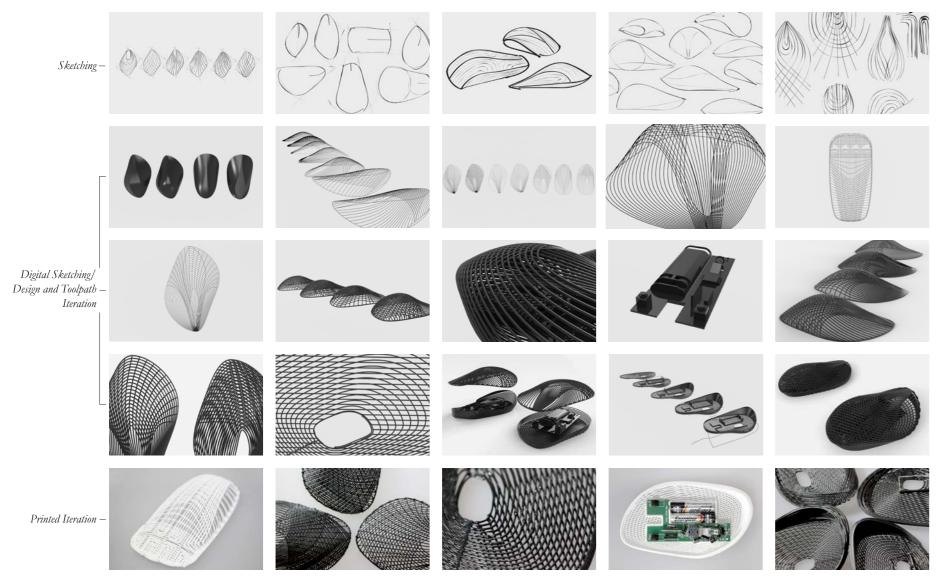


Figure 107. Author, AE2 Development Process

### MOUSE DESIGN DEVELOPMENT



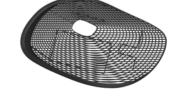
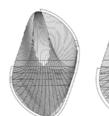


Figure 108. Author, Mouse Top Piece

Figure 109. Author, AE2 Mouse Base Piece

exploration of both mechanical, and touch sense interactions. have useable buttons and general functionality. (Figure 110) It was tested and proved that the sensor worked under a layer

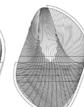
The application of a mouse and its componentry provided defined of printed plastic, and developed so that the sensor could be structural and ergonomic restraints and requirements. Different implemented directly during. Material directions were utilised for types of mice were researched for their electronics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

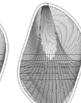


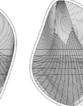


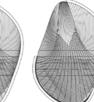


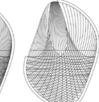
















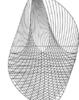


Figure 110. Author, AE2 Toolpath Iteration



3.2

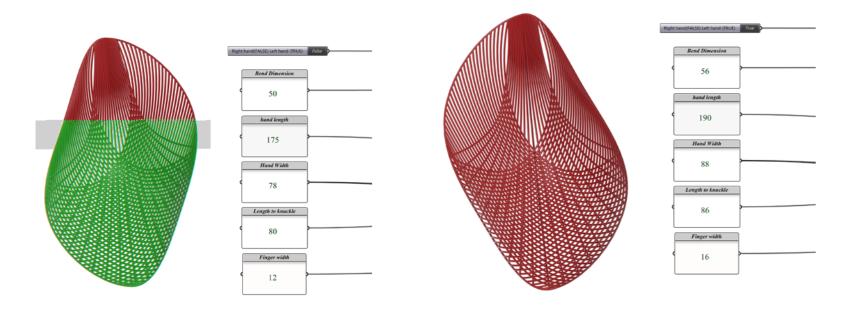


Figure 111. Author, AE2 Hand Dimensions 1

Figure 112. Author, AE2 Hand Dimensions 2

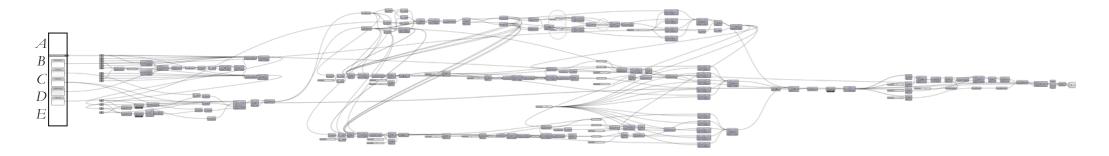


Figure 113. Author, AE2 Parametric Model

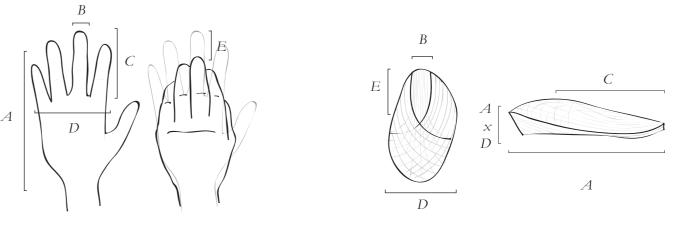


Figure 114. Author, AE2 Parametric Relationships Bewteen Hand and Mouse Dimensions

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.

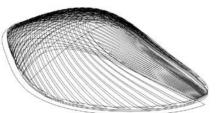
Dimensions here were manually measured and put into the grasshopper script, but a more intuitive processes could be used to implement these values. Feetz (n.d.) is 3D Printing Shoe service which allows for customisation. They use an app to measure user dimensions digitally. A similar approach to digitally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



3.2

135 Figure 116. Author, AE2 Mouse Assembly

## Tab details for holding electronic componentry

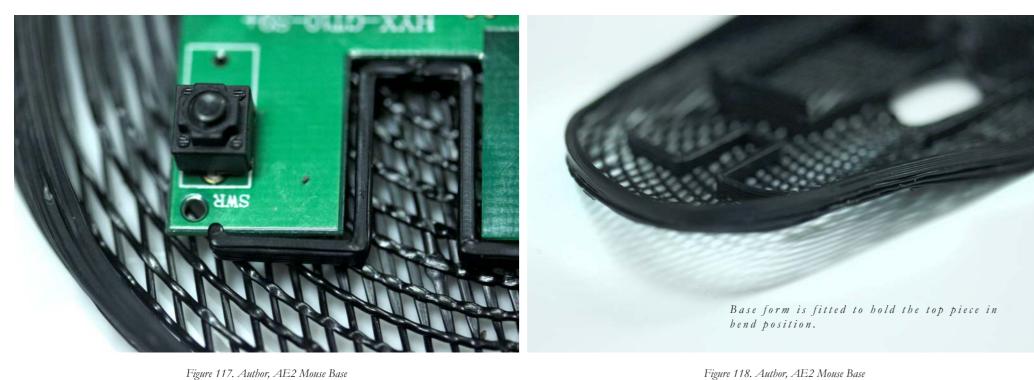
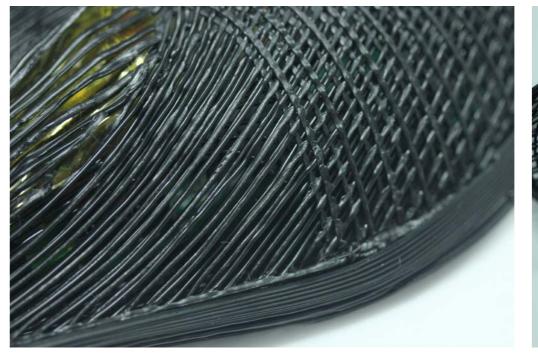


Figure 117. Author, AE2 Mouse Base

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



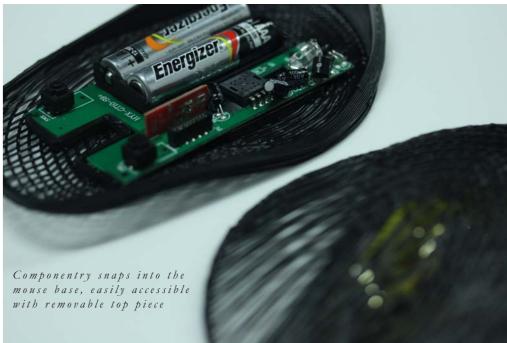


Figure 119. Author, AE2 Mouse Assembly Figure 120. Author, AE2 Mouse Base and Top



### 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.

1 3 9 Figure 121. Author, AE3 Printed Iteration

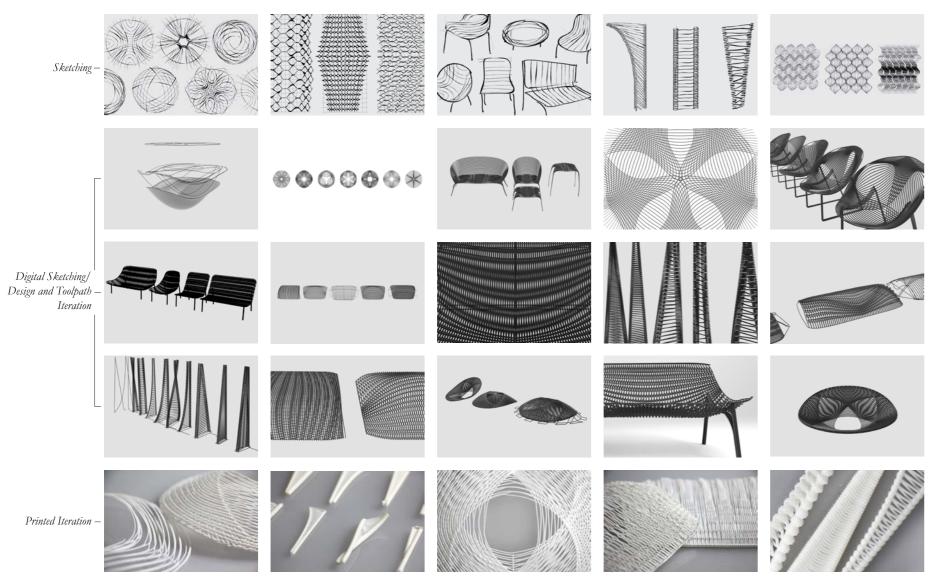


Figure 122. Author, AE3 Development Process

### 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

flowed lines allowing for variable visual and physical effects.

## 3B - LINEAR (DIS)ARRAY

The first parametric series began to build upon overlay qualities This patterning system was in seeking of new repetition based. A generative use of patterns was also used to create leg found in previous experimentation. Design development found approaches that hadn't yet been explored. The creation of this structures. These structures were to be used conjunctively with interesting qualities when using multiple pattern or repetitious patterning system became reflective of woven textiles. Linear parts 3A and 3B of the application based experiments (3.2). For geometries conjunctively. A set of repetitious lines were first patterns in two directions interact with each other create textural structural necessity, a partially layer based system was used to defined, becoming subsequently rotated around a central structures. This was produced from two sets of repetitious, create compact form. They also utilised freeform techniques and axis. In this series variety of structure became easily controlled. uniform curves. One curve set was then used to split and rebuild patterning to allow the structures to reflect the qualities of the Deposition flowing in the same direction provided flexibility and the other, to create variability in structure. The series pursued overall furniture piece. The script for the legs became integrated overlaid materials more strength. The arrangement of overlaid vs to find implications for variable material qualities, through the to the scripts of the main furniture structures, 3A and 3B. This convergence and divergence of lines.

### 3C - PARAMETRIC LEG STRUCTURES

meant that the legs could be placed and adjusted to respond to existing defined geometries, both functionally and visually.

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### POLAR OVERLAY - PARAMETRICS AND CUSTOMISATION

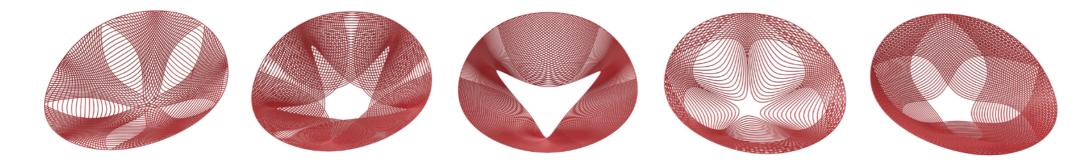


Figure 124. Author, AE3a Parametric Output Exemplar

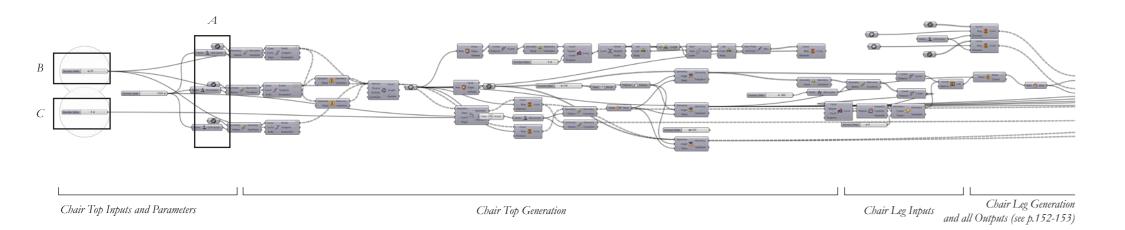
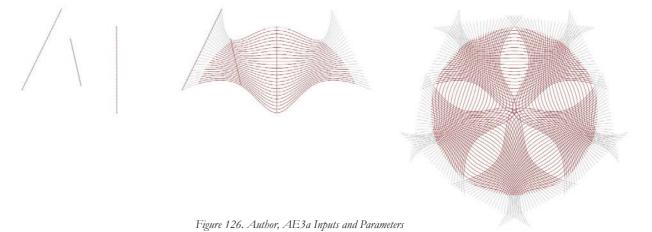


Figure 125. Author, AE3a Parametric Model



### INPUTS & PARAMETERS

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

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

Number of rotations in Polar Array of curves made in B

In this system, first defined are a set of curvilinear and repetitious through just 3 inputs adjustments. This system does, however, parameters can create a large range of patterned outputs with formation. various implications on printed aesthetics and physicalities, here

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

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## LINEAR (DIS)ARRAY - PARAMETRICS AND CUSTOMISATION

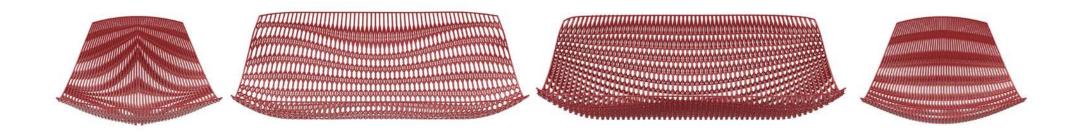


Figure 127. Author, AE3b Parametric Output Exemplars

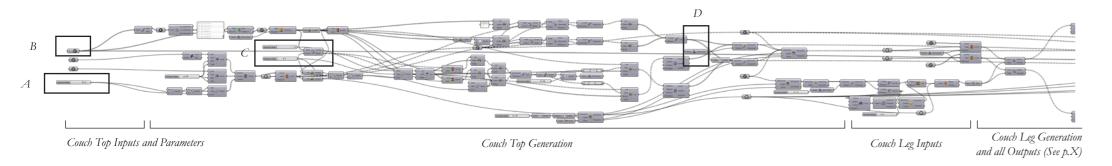
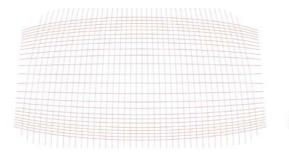
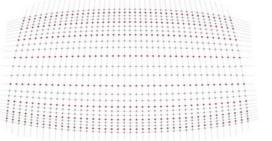


Figure 128. Author, AE3b Parametric Model





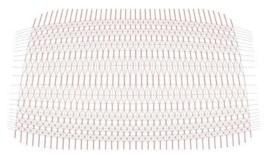


Figure 129. Author, AE3a Inputs and Parameters

### INPUTS & PARAMETERS

A (Grev 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.

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.

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 surface form. A new curve is then defined with integration of the selection of every third point. The chosen points are then moved furniture forms could be produced. both towards an adjacent point, and away from the underlying

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

# 

Figure 130. Author, AE3c Parametric Output Exemplars

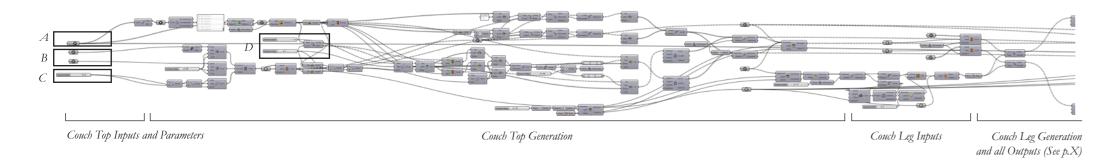
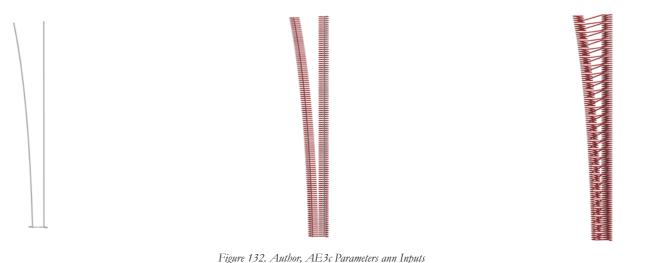


Figure 131. Author, AE3c Parametric Model

### LEG STRUCTURES -PARAMETRICS AND CUSTOMISATION



INPUTS & PARAMETERS

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

up, creating the structure and geometry of the edges

Layer height - the main curves (A) are split at increments of an Toolpath Pattern-The two profile curve lists defined (C) are inteinput height to define layer offset. The profile curve is then copied to grated into a pattern adjustable by the user. This pattern defines each of these increments.

the path of curve interpolation.

Custom profile curve - the curve defining the profile to be layered

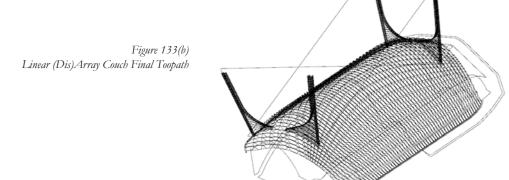
by an adjustable pattern. (D) The defined pattern controls the final piece would sit flat on a surface when upright. order in which the profile curve layers are printed. These curves

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

# 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



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

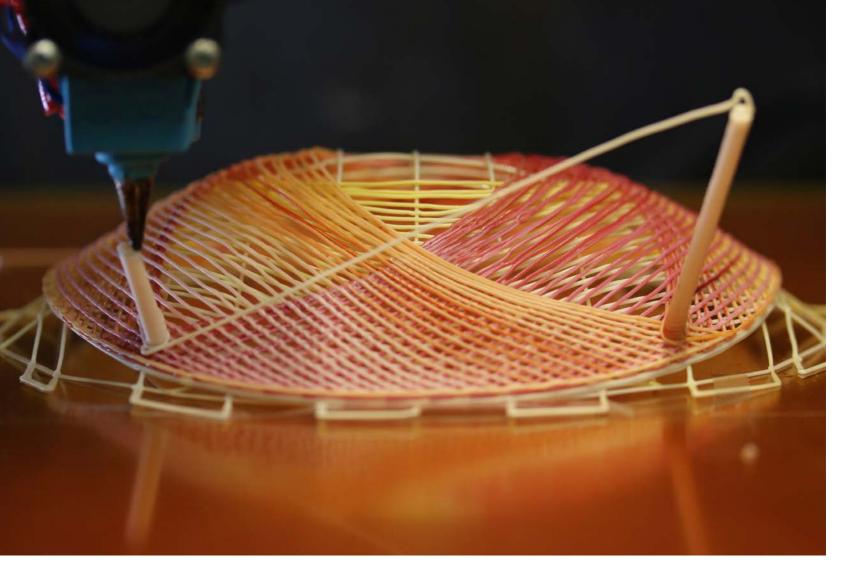


Figure 134. Author, AE3 Chair Printing



Figure 135. Author, AE3 Chair Figure 136. Author, AE3 Chair

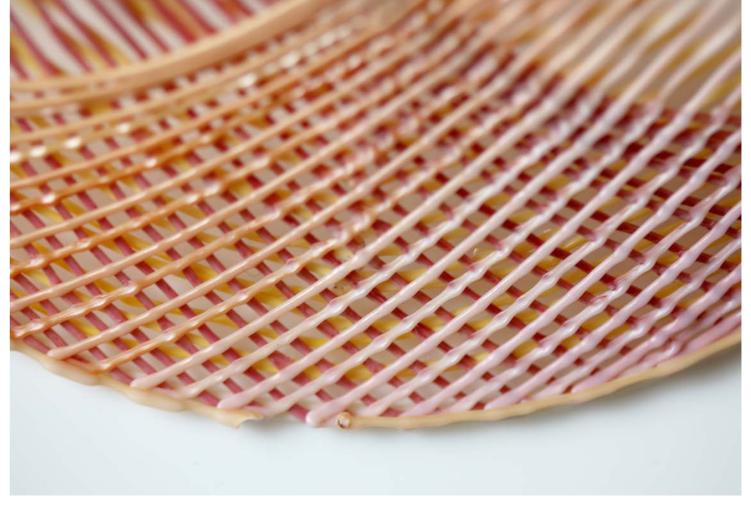


Figure 137. Author, AE3 Chair

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

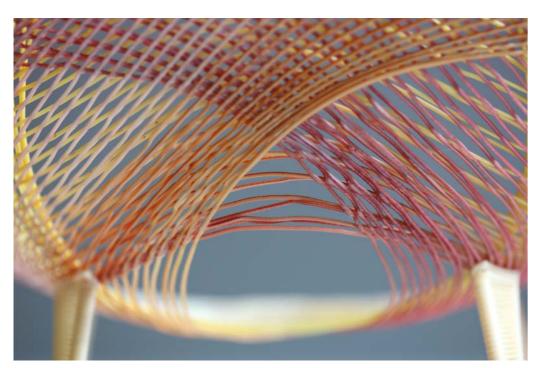


Figure 138. Author, AE3 Chair

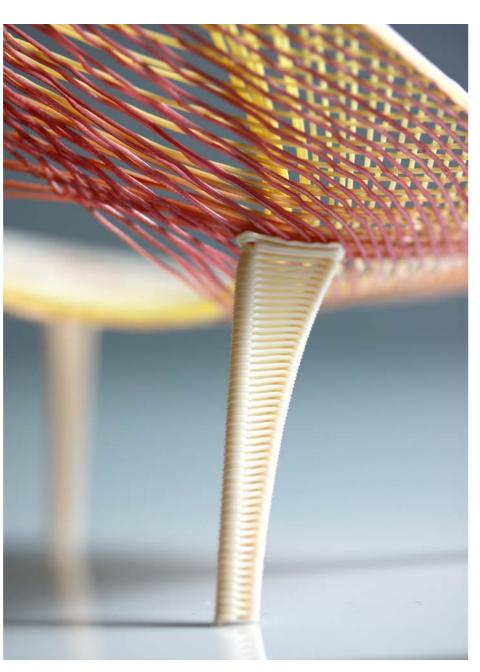


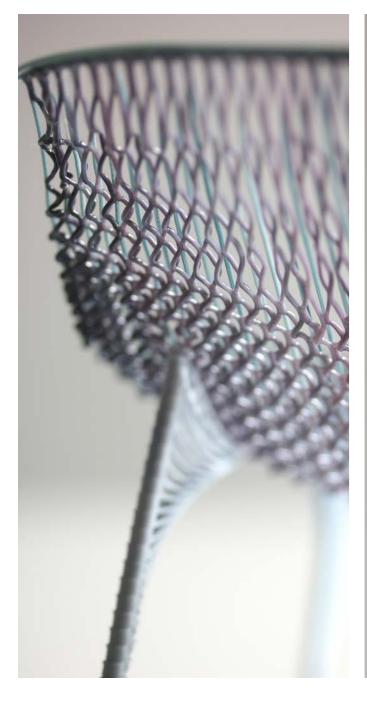
Figure 139. Author, AE3 Chair and Leg Structure



153 Figure 140. Author, AE3 Couch

Patterning and tectonics of the couch model

3.2



Application



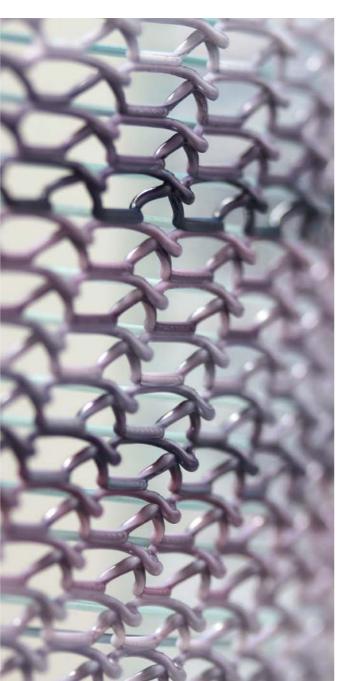




Figure 144. Author, AE3 Couch

155 Figure 141. Author, AE3 Couch Figure 142. Author, AE3 Couch Figure 143. Author, AE3 Couch

### DESIGN PHASE 2 CONCLUSION

The creation of the application based experiments was a highly interactive process and a very intimate relationship with approached through unique perspectives for each artefact. the manufacturing device. The development of a design became Designed with synchronous consideration of material deposition a negotiation of the designer and the limitations and the intended output the series begun with unique starting of the printer. A conversation of design iterations continued until points. Series 1 and 2 heavily responded to the brief and needs the craftsman (the designer) the workman (the printer) and the of its artefact for informed material deposition techniques. In material could agree upon a solution. Listening and watching the opposition, Series 3 begun with abstracted material formations, to printer and material became a method of research in its own right. be designated the role of an object subsequently.

Through these object, electronic and furniture based pursuits it understanding allowed the authorship of the method of making was understood how widely impactful material deposition is to be reclaimed, and the printer to become a palpable tool for the integrity of its printed artefact. Interesting visual, physical and actualising digital craft. Computational systems and digital design tectonic qualities were found through various deposition design tactics became of high regard. Diversity in digital techniques formations. Even so, many more opportunities lay dormant. A resulting in diversity in artefacts, both between prints, and locally handful of techniques were explored comprehensively. Overlays of within single designs. Direct and Parametric modelling techniques repetitious lines, three-dimensional layering, and other patterned worked with lines, surfaces and forms to develop artefacts that techniques became revered, both individually and accumulatively. embrace and respect its method of making and disregard any There are countless more opportunities for Designed Deposition. predetermined assumptions about how it should be constructed. 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

Sounds and signs expressed the comfort of the printer, becoming information towards future designs. This relationship and

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

up. The value of AM for one-off forms allows for customisation experiment 3. 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

Artefacts were developed through an Industrial design perspective. Through generative design processes, product users can gain They sought notion towards, but not the development of, final control over the quality of output. Here, user input was considered design products. Materials, durability and consistency became another influencing factor towards the design of material deposition clear factors inhibiting further the success towards end product with regards to its output and user from commencement. Simple user quality. However, in embracing the manufacturing tectonics there interactions, available through parametric modelling, were found to becomes exposition of new tools to enhance design quality in grant large adjustments for ergonomic, visual, and structural influence novel ways. Enhancement and intricacy of form, tactility, interaction, from its user. The use of customisation through digital mediums and and aesthetic based qualities were engaged with throughout the AM has been discussed by Gershenfield (2006) to benefit multiple explorations. The diminished need of support material heightens areas. Including for allowance of the embodiment of self, 'personal the potential economic value of material and time compared expression in technology that touches passion: (16:50), such as to other AM methods, and largely reduces post-print clean- explored through the highly adjustable models of abstract based



PART 4



4.1 - COMPARISON OF MANUFACTURING METHODS

Reflection

### 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

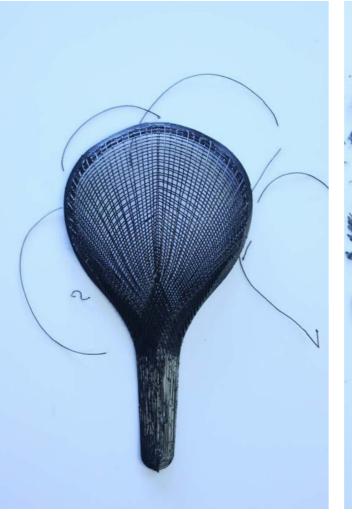


Figure 145 (b) Designed Deposition Print

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.

contact of support structures, and the exposed upward faces and material quality more appropriate to the final artefact. which had areas of successful detailing. The print orientation of

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

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

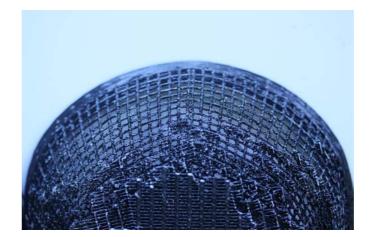


Figure 146(a) FDM Print Oriented Facing Up Detail

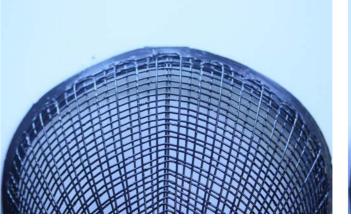


Figure 146(b) Designed Deposition Print Detail



4.1

Figure 146(c) FDM Print Oriented Facing Down Detail

4.2 -DISCUSSION

### OVERVIEW

Freeform 3D printing provided this research with opportunistic making. The process no longer seeks to produce any input capacity for new approaches to building additive 3D forms. form, instead only those which respect and embrace both the Common approaches to defining material deposition were opportunities and limitations of their manufacturing method. disregarded, opening space for new techniques for building form. A research through design methodology was adopted for the Self-supporting build material and fully simultaneous motions were exploration of possible techniques and applications of Designed tools utilised, revealing both promising opportunities and novel Deposition. The Abstract Design Experiments (2.2) began to limitations for the creation of extrusion-based AM artefacts.

This research illustrates that a designer with the ability to learn experiment, be it 'successful' or not, presenting constructive the language of appropriate CAD and CAM technologies can information. These experiments began to explore possible become an informed mediator between the digital and the new computational systems, utilising both direct and parametric physical, directly defining three-dimensional built form through modelling techniques. Designs were created with lessened the design of repetitious curves. The designer can reclaim control regard to its output. Instead, there is focus on both visceral and of the manufacturing method from automated algorithms, making technical value gained from its Designed Deposition. it an intrinsic part of crafting artefacts. Deposition is curated with consideration of aesthetic, functional and tectonic qualities in both The findings of the Abstract Design Experiments (2.2) informed form and materiality. Intended use and intended user interaction the subsequent Application-Based Experiments (3.2). These becoming integral with Designed Deposition and the material experiments were not intending to create final products, but is crafted with consideration of these and various other aspects pursued further knowledge on the process and its applicability specific to it's artefact.

Some beneficial features of AM were, however, impacted by this product and user-based requirements could be obtained through new technique. Undercuts became increasingly difficult to execute freeform 3D printing. Illustrated was just how influential material when a strict ground-up basis was not utilised and the complexity deposition was in the variation of both visual and physical factors. of form was restricted. While form may become restrained in some Values of density, tactility, materiality, ergonomics and structure circumstances, the qualities of materiality, aesthetics, structure and were tailored to create one-off creations as well as those which tactility gain the capability to become revitalised and diversified. were customisable on the mass scale. it was explored how This research illustrates 3D printing's capability for informed parametric design could allow users to customise factors including deposition, revealing potential for its application in the production aesthetic quality and structural variability. This integration of user of bespoke products, not only rapid prototypes. Designed input furthers the concurrent consideration of both the user and

discover possible print tactics of significance, as well as identify areas of restraint. Each series had a unique focus, and each

through self-defined direction and context. Object, electronic and furniture based outputs were developed to show that various Deposition allows artefacts to thrive through the method of their the output when designing an artefact and material deposition.

### BROADER IMPLICATIONS

Performed through standard 3-axis FDM printers, this research. The implications of this technique extend further than that sought to discover the implications of the spatial printing method specifically found of this, or other individual research. compared to its largely explored 6-axis counterpart.

respect of the method of making, accepting this process for material efficiency developed further still. bespoke and specific creations that embrace both opportunities and limitations presented of the process.

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 Other advantages of AM in general are tool-less production, local technology or knowledge.

'designer' and 'user'. Recent design methodology has and energy usage. 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)

A major insinuation of the freeform process is the curated and The main impediment, as anticipated, was the lessened dexterity vastly reduced use of material and energy. The immensely that allows for undercutting and the ability to manoeuvre around decreased and often non-existent requirement for support material existing geometries with greater freedom. As aforementioned, allows for AM to become much more sustainable in the use of this can limit geometry and complexity of an intended artefact. material. Informed material deposition and only placing material Through tactical strategies, some geometric restraints could where necessary sees this further exhibited. The implementation be overcome. However, artefacts and forms were chosen with of technologies such as finite element analysis (FEA) could see

For these same reasons, printer motions are also decreased. While this seems unimportant, the implication for future is largely The value in using this simpler technology lies in its exposition reduced print times. Through this research, printer motions during of the process to a more inclusive audience. A high level of three-dimensional movements were extremely slow to allow for specialised knowledge and equipment are required to integrate material to cool and self-support. In other research, printer speed and control both a robotic arm and a custom extruder, compared has been increased through technology development. This is to the already equipped FDM printer. The limited size and dexterity most commonly achieved through integrated cooling systems, of a standard printer could be seen as impediments in some and also by creating steady temperatures and higher torque. contexts, however as a cheaper, more accessible, and easier to (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.

printing. Software development and inclusion of both 3 and printing, and lessened transport. Once setup, the necessities of 6-axis technology could begin to democratise the adoption of AM requires no physical inventory apart from the input of material. this process, becoming inclusive audiences without specialist. 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 The most significant boundary currently not only being extrusion methods could in future find benefits towards the merge crossed but being dismantled is the boundary between in these technologies with larger scale production. Other benefits professional and amateur, or more pertinently, between of the process are reduced post-print cleanup, labour, material

### LIMITATIONS

Figure 147. Author, Print Failures

### Technical/Physical Limitations

themselves, however, there was a risk of reduced reliability. Figure industrial design factors were prominent influences. 147 expresses a small sample of the many print fails that occurred during the research.

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 This research sought input from users to engage with the material from oozing out.

one for freeform movements. Advancement of these relationships improve validation of choices. 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

The process sought opportunities to repurpose the contexts and Material deposition and the delineation of form were impressed abilities of AM. By shifting away from automation, the research by many factors. Required shapes of intended outputs, the showed that new possibilities for improvement presented aforementioned physical and computational limitations, and

The interpretation of these influences into digital structures and printed artefacts was largely influenced by the design sensibilities Generative methods largely aided the creation of models which of the author. If the same area was explored through a different were found to be both editable and adaptable relatively easily. design perspective, the discoveries would have differed The main hindrance became the limited capacity of the self-made substantially. Input from the research supervisor and other computational scripts. Advancement within the digital realm would external parties helped to provide fresh insights for utilisation be beneficial for greater interpretation between curves, motions, 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.

of systems that are able to define motions, without extrusion. This deposition of material, and considered their interaction with the generally requires reverse extrusion to quickly stop and extra 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 Improvement would also be found through higher intricacy of the imparted by using the author's design values. Lack of gaining a relationships between curve geometries and their correlating range of perspectives from potential users through testing and extrusion and speed rates. In this research primarily two feedback became a limitation for the full comprehension of user relationships were defined. One for planar, supported printing, and sensitive design. The implementation of user feedback would

### FURTHER RESEARCH

### Future Development

Technical and physical development became seen as the primary Designed Deposition takes away the security of layer-based area for future research to note. Through this evolution, there may techniques meaning for more specific and less inclusive outcomes become more tools for deposition and allow for more applicative as rapid prototyping. Even so, it could still be host to a large range values to be discovered. Specific areas to develop upon may of output opportunities. This research attempted to present a include;

- improvements would rapidly increase the feasibility of this process become appropriate uses of the process; towards end product production.
- range of materialities.
- -The greater complexity of toolpath creation strategies and Lighting With the focus on the effect of toolpath and material manufacturing information scripts to increase the ease of creating deposition and density, interesting effects could be found to structures and geometries.
- Integration of finite element analysis (FEA) into the process could be a valuable technological resource for the deposition of material. - Exhibition Equipment - The scalability of the process could see time and material, and for justified placement of the structure.
- Upscaling and experimenting with the implications during an Signage or Branding The process could be used as a new increase in size.

### Further Applications

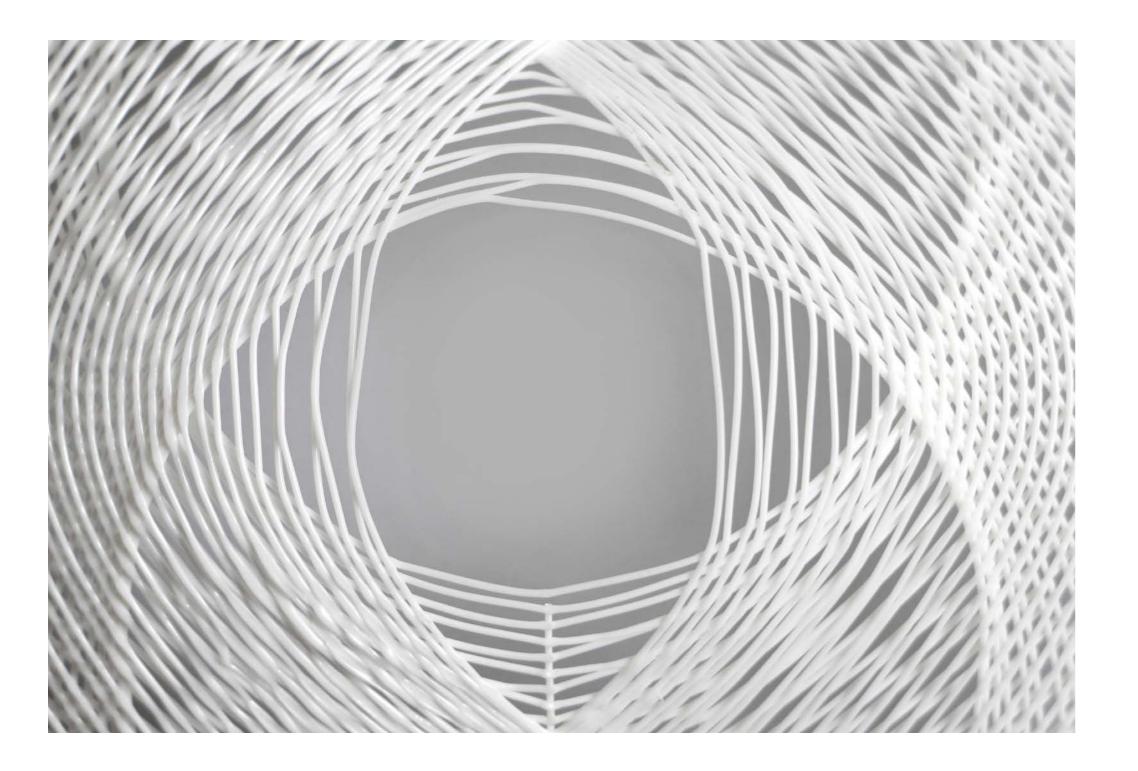
range of possibilities for Designed Deposition through a small handful of contexts and application. Throughout the duration of - Material research; creating, developing, and blending new the study, alternative opportunities were also considered, as well materials seems of great advantage to the area. Development as further development of current areas. Within realm of the smallof self-supporting and fast setting substances with structural mid scale industrial design context, the following areas could also

- Full-scale Furniture Creation of furniture at full scale, such - Exploration of multi-material prints for to allow provision for through the proposed Application Experiments 3A, 3B &3C, and increased opportunity for multi-functional outputs with increased the development of mid-scale designs found if printing at an increased scale.
  - impact light quality. Clear materials could be utilised as light pipes/
- This provides increased consideration to the sustainable use of bespoke and responsive stands, hangings or surfaces that could be informed by both intended context and exhibited works.
  - 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).



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### All figures not cited here have been produced by the author

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APPENDIX A

Precedent Research Matrix

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### APPENDIX B

Precedent Technical Factors Infographic

Frequent D Printing:

Autonomous Tottnite MXID - Reis

Autonomous Tottnite Printing

Autonomous Tottnite

Autonomous Tottni ABS ABS used, PLA PLA and HDPE ABS Fast coring resin High Denisty polythylene ABS Metal; Steel, aluminium, ABS, PLA also KUKA KR125/2
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DESIGNED DEPOSITION
Freeform 3D Printing for Digitally Crafted Artefacts

Isabella Molloy