ROBOTIC SPATIAL PRINTING FOR DESIGNERS

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ABSTRACT

This research developed a fully-integrated robotic printing system, using new methods of additive manufacture (AM) that enables users to explore spatially printed structures with increased freedom of geometric complexity.

Current AM technologies, such as Fusion Deposition Modelling (FDM), can rapidly translate design ideations into solid forms by precisely depositing consecutive layers of material in coordination with the movements of a robotic platform. Using this method, solid objects are digitally deconstructed into linear toolpaths and physically reconstituted with thermoplastic extrusion equipment; the toolpath becomes the form.

Spatial printing, using methods such as those demonstrated in this research, offers a new way of building 3D forms. By harnessing the potential of FDM equipment and materials for generating self-supporting structures, the user can create complex free-standing structures unshackled from the layered constraints of typical additive manufacturing processes. Here, the user acts as an informed negotiator between digital form and physical manifestation where movement realises form.

A complete spatial printing system was built that harnesses the complexity of robotic movements and responds to the needs of printing materials through a feedback loop that draws from the results of experimentation. Bespoke printing equipment and computational processes strive to improve the craft qualities and printability of input materials with a specific focus on compatibility with co-extrusion biopolymer filaments developed by Scion. This thesis illustrates the development of a versatile spatial printing system and subsequent investigations into the craft qualities and freedom of complexity that this system offers to designers and architects.

ACKNOWLEDGEMENTS

I would like to thank my supervisors Tim Miller and Kevin Sweet for their unwavering patience and investment in my studies. The experience and learning I have gained from this project is invaluable to me.

To my parents, Deb and Dai, for their unconditional support and encouragement. I would never had made it this far without you.

My thanks to Ben, Devon, and John for your resources and technical assistance. Your craftsmanship and generosity has been an inspiration to me.

To my friends here and the world over for your steadfast love and support. You raise me up to new heights and make it a joy to pursue your passions.

CONTENTS

TERMINOLOGY

PROJECT-SPECIFIC TERMS

FREEFORM PRINTING

A method of additive manufacturing that uses extrusion equipment to print self-supporting 3D structures by solidifying thermoplastic materials immediately post-extrusion. Originally coined as part of a paper titled “Freeform 3D Printing: toward a Sustainable Approach to Additive Manufacturing (Oxman et al., 2013)

SPATIAL PRINTING

Can be used interchangeably with the term “Freeform Printing” but describes any printing movement that exploits simultaneous X, Y, and Z movements through Euclidean Space

NODE

A point in a network or diagram at which lines or pathways intersect or branch

EXTRUSION

v. The action of thrusting or forcing something out
n. Something that has been shaped by being forced through a die

HOTEND

A region in the printing tool where the materials are heated enough to become flowable. Usually fed by an extruder and separated from other componentry by a cooling mechanism that keeps the heat confined to a specific area

FEED-RATE

The speed at which a machine is fed material or power. In the case of 3D printing, the speed at which material is fed by the extruder into the hotend

MANUFACTURING

AM - ADDITIVE MANUFACTURING

Any of various processes in which material is joined or solidified under computer control to create three-dimensional objects

3D PRINTING

Used interchangeably with Additive Manufacturing

FFF - FUSED FILAMENT FABRICATION

An additive manufacturing (AM) technology commonly used for modeling, prototyping, and production applications. FFF operates by laying down material in layers until a form emergers

CAM - COMPUTER AIDED MANUFACTURE

The process of manufacturing objects using a digital workflow and CNC machine tools

CAD - COMPUTER AIDED DESIGN

The automation of machine tools by means of computers executing pre-programmed sequences of machine control commands

MATERIALS

ABS - ACRYLONITRILE BUTADIENE STYRENE
PLA - POLYLACTIC ACID
PET – POLYETHYLENE TEREPHTHALATE
PTFE - POLYTETRAFLUOROETHYLENE

COEXTRUSION

The process of pressing materials through the same die to produce a single piece

FILAMENT

A slender threadlike material or fibre, used in this research as the material feedstock for extrusion

TERMINOLOGY

DIGITAL MODELLING

PARAMETRIC DESIGN

Parametric design is a process based on algorithmic thinking that enables the expression of parameters and rules that, together, define, encode and clarify the relationship between design intent and design response

BIOMIMETIC

Biomimetics is the imitation of the models, systems, and elements of nature for the purpose of solving complex human problems

FEA - FINITE ELEMENT ANALYSIS

Finite element analysis is a computerized method for predicting how a product reacts to real-world forces, vibration, heat, fluid flow, and other physical effects. Finite element analysis shows whether a product will break, wear out, or work the way it was designed

NURBS - NON-UNIFORM RATIONAL BASIS SPLINE

NURBS are mathematical representations of 3 D geometry that can accurately describe any shape from a simple 2 D line, circle, arc, or curve to the most complex 3 D organic free-form surface or solid. Because of their flexibility and accuracy, NURBS models can be used in any process from illustration and animation to manufacturing

COMPONENTS & CONTROL

PLC - PROGRAMMABLE LOGIC CONTROLLER

An industrial digital computer which has been ruggedized and adapted for the control of manufacturing processes, such as assembly lines, or robotic devices, or any activity that requires high reliability control and ease of programming

ADC - ANALOG-TO-DIGITAL CONVERTER

Used in electronics as a system that converts an analog signal, such as a sound picked up by a microphone or robotic control signal, into a digital signal

LED - LIGHT EMITTING DIODE

A semiconductor light source. LEDs used in this research have controllable red, green, and blue channels to display a full spectrum of RGB colours

PID - PROPORTIONAL INTEGRAL DERIVITAVE CONTROLLER

A control loop feedback mechanism widely used in industrial control systems requiring continuously modulated control. A PID controller continuously calculates an error value as the difference between a desired setpoint (SP) and a measured process variable (PV) and applies a correction based on proportional, integral, and derivative terms (denoted P, I, and D respectively). Use in this research to control the temperature of the hotend

TCP - TOOL CENTER POINT

A point used by the robot to calibrate the positioning of the end of an attrough the same die to produce a single piece

CODE EXAMPLES

G-CODE

G-code is the name for a text based numerical control programming language, mainly used to control automated machine tools. G-code is used in this research to command the programmable logic controllers that control the extrusion process

EXAMPLE START

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

EXAMPLE BODY

```
G1 X146.498 Y13.750 E0.1426 F1800 ;
G1 X146.525 Y13.664 E0.1462
G1 X146.984 Y12.668 E0.1900
G1 X147.032 Y12.591 E0.1936
G1 X149.283 Y9.816 E0.3362
G1 X149.348 Y9.754 E0.3398
G1 X150.229 Y9.100 E0.3836
G1 X150.307 Y9.056 E0.3872
```

EXAMPLE END

```
M104 S0 ; turn off extruder
M140 S0 ; turn off bed
M84 ; disable motors
```

RAPID CODE

RAPID is a high-level programming language used to control ABB industrial robots

EXAMPLE CODE

```
MODULE MainModule
! ============== DECLARATIONS ===============
VAR speeddata s1:=[4000,100,5000,1000];
VAR triggdata p1;
VAR triggdata p2;
VAR triggdata p3;
VAR triggdata p4;
VAR triggdata vSet1;
VAR triggdata vSet2;
VAR triggdata vSet3;
! =============== PROCEDURES ===============
PROC Main()
ConfJ \Off;
ConfL \Off;
TriggIO vSet1, 0\Aop:=aoVUW_1, 2;
TriggIO vSet2, 0\Aop:=aoVUW_2, 4;
TriggIO vSet3, 0\Aop:=aoVUW_3, 6;
TriggL p1, s1, vSet1 \T2:=vSet2 \T3:=vSet3, z1, GripperLED\
WObj:=WObj0;
TriggL p2, s1, vSet1 \T2:=vSet2 \T3:=vSet3, z1, GripperLED\
WObj:=WObj0;
TriggL p3, s1, vSet1 \T2:=vSet2 \T3:=vSet3, z1, GripperLED\
WObj:=WObj0;
TriggL p4, s1, vSet1 \T2:=vSet2 \T3:=vSet3, z1, GripperLED\
WObj:=WObj0;
ENDPROC
ENDMODULE
```

BACKGROUND RESEARCH

LITERATURE REVIEWS

ADDITIVE MANUFACTURE

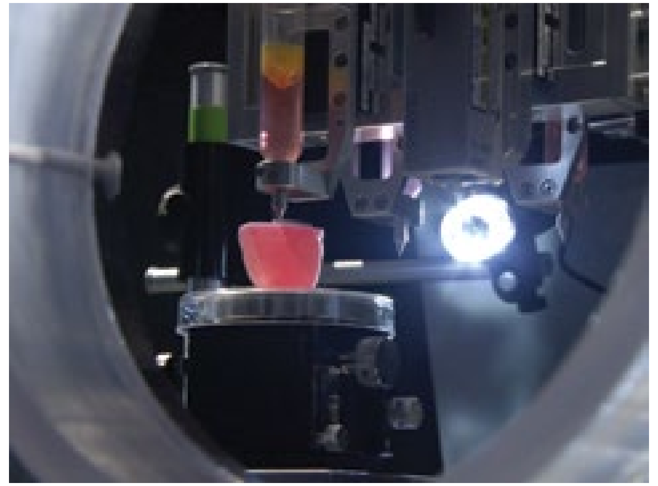


Figure 1: 3D Printed Kidney(Atala, 2011)

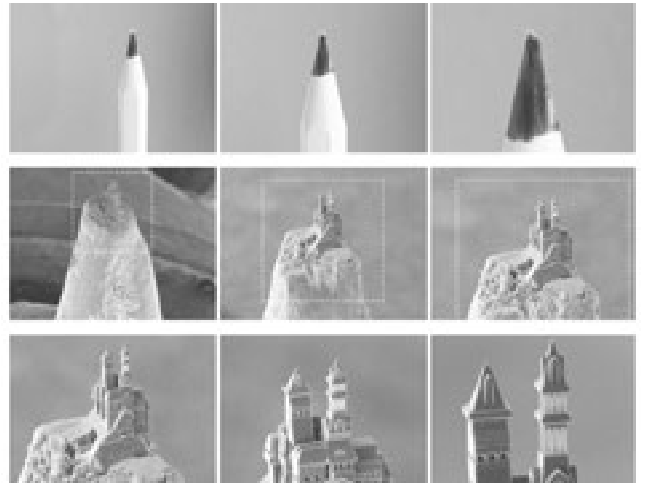


Figure 2: Multiphoton Lithography (Stampfl et al. 2016)

Figure 3: VULCAN Pavilllion (Laboratory for Creative Design, 2015)

Additive manufacturing emerged in 1983 when Chuck Hull created the first 3D part using his stereolithography process, a promising method for automating fabrication and construction (3D Systems 2018)(Jacobs, 1992). AM has since been the subject of significant interest from industry, academia, and the general public for its capacity to deliver intricate and complex physical forms built from a variety of tailored materials including plastics, ceramics, metals and biomaterials with minimal waste and processing. In combination with computer-aided design (CAD), additive manufacturing can fabricate custom digitally-designed objects locally, quickly, and made to specifications without the usual high production numbers and tooling expenses of traditional manufacturing processes. Armed with a 3D printer and a computer, designers, architects, artists, doctors, and lay-people to name a few now have the means to unreservedly print a wealth of custom objects from pancakes to pancreata on the scale of a pin-head to a pavilion. (Figure 1, 2, 3)(PancakeBot, 2017)

Additive manufacturing situates itself between mass and artisan manufacture, combining the digital precision and repeatability of a factory floor with an artisan's design freedom. A 3D printer is automated in the sense that it is instructed by a design file that succinctly captures instructions for the manufacture of a particular product; that information can be saved, copied, and sent anywhere to be modified or used again. Like a human artisan, a 3D printer is versatile. A printer can fabricate a variety of different types of objects quickly without significant upfront investment and incurs no penalty for printing a thousand of the same object or the same number of unique objects - the cost of customisation nearly disappears (Fabricated 2013).

These advantages, and the numerous breakthroughs in 3D printing technologies, should see widespread adoption of additive manufacture in the design community and could even grow to replace many of the manufacturing supply chains in the industry but for a few limiting factors. Additive manufacturing offers no economies of scale, produces objects of modest size in a modest time and often lacks the mechanical or design qualities desired of an end-use product. One can certainly attribute these shortcomings to the fledgeling nature of additive manufacturing technologies, yet AM's surge of growth and its ability to manufacture small numbers of unique, constantly changing and customised objects lends it to more informed, specialised, and artisan applications in which this research is interested.

Figure 4: Radiolaria Pavillion (Shiro Studio, 2008)

Figure 5: 3DPRINTCANALHOUSE (DUS Architects, 2015)

Figure 6: Digital Construction Platform (Keating, et al.,2017)

Additive Manufacturing's first truly large-scale 3D printer made its debut in 2008 with Enrico Dini's D-shape printer. A building-sized gantry system capable of printing 3x3x3m structures in artificial sandstone, the D-shape introduced the design freedom of additive manufacturing to architects as a prototyping tool for building architectural scale structures as demonstrated by Shiro Studio's Radiolaria pavilion (Figure 4). Creating complex self-supporting 3D printed structures was previously unachievable in architecture, and Dini was enamoured by the prospect using his printer to reproduce natural materials using the same building principals as nature as an "instrument to achieve beauty"(Twigg,2016).

"One night in 2004 I couldn't sleep and I had this vision of what 3D printing could do, it was a dream of amazing shapes. A dream of beauty. Beauty, you see, is the essence of life – it is not an option, it is everything."– Enrico Dini

The successes of projects like the D-Shape sparked interests worldwide with a rise in projects aiming to take additive manufacturing to new heights and explore the potentials of building large-scale with newly tailored materials (Bos et al.,2016). For example, DUS Architect's KamerMaker explored the proto-architectural applications for large-scale additive manufacturing with their 3D Printed Canal House made from bio-based plastics (Figure 5), and Contour Crafting created a system for printing liveable concrete houses for use both on earth and extra-terrestrially (Contour Crafting, 2018). Going further still, MIT integrated additive manufacturing processes into their Digital Construction Platform (DCP) – a mobile robotic platform which with a series of interchangeable end-effectors including a plastic extruder and expanding foam sprayer allowing them to print the skeleton of a whole building autonomously and in-situ with no theoretical limits on size and complexity (Figure 6). Successes in construction practice saw an increased interest in large-scale AM in the manufacturing community such as Ford Motors' partnership with Stratasys to test their "Infinite Build" 3D printer; Using FFF and an industrial robot arm the project rapidly prototyped interiors for new car models and functional aeroplane parts with no theoretical boundaries in build volume. Ford could then test these full-size prototypes as a part of the development process (Abuelsamid, 2017).

Although many of these projects have demonstrated effective methods of 3D printing on larger scales, each of them reaches a ceiling of critical limitations that arise from the layered printing process. "Cost, accuracy, and strength of 3D products need to be overcome before this technology can achieve widespread adoption" (Sherman, 2009). Strength is particularly important for mechanical or load-bearing structures such as those in automotive, aerospace, architecture or construction, and issues relating to weak bonding between printed layers can lead to delamination and breakage under stress (Berman, 2012). Additionally, the accuracy of 3D printed parts would need to be around ten times as precise before it can compete with industrial engineering processes, particularly with functional mechanical parts (Rudd, 2011).

Figure 7: Freeform 3D Printing (Oxman et al., 2013)

Figure 8: Extruded Structures (Thoma et al., 2015)

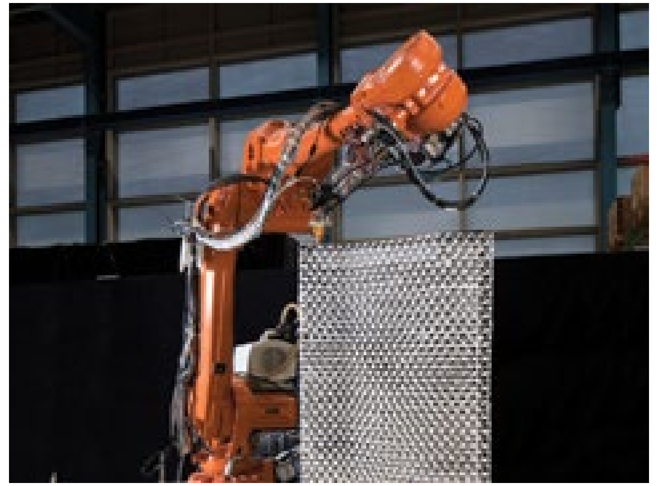


Figure 9: Mesh-Mould (Hack & Lauer, 2014)

FREEFORM PRINTING

Freeform printing is an evolution in additive manufacturing that offers new approaches to building 3D forms. Maintaining much of the design qualities of its parent technology, freeform printing derives from fused filament fabrication (FFF). FFF is currently one of the most widespread forms of additive manufacturing whereby a machine extrudes a bead of material along a planar toolpath in thin layers, and each successive layer fuses with the previous until a form emerges (Hod & Melba, 2013). Similarly, freeform printing extrudes material along a toolpath but escapes the layered constraints of FFF by solidifying that material immediately post-extrusion; this enables freeform printing to attempt more complex forms with the potential for self-supporting structures by depositing material at any point within the CNC machine's reach in free space.

The Mediated Matter Group at MIT coined "freeform printing" in 2013 as a part of the project Freeform 3D Printing: Toward a Sustainable Approach to Additive Manufacturing (Oxman et al. 2013). Most additive manufacturing technologies use support materials in the fabrication process that are both wasteful and time-consuming to print, so they developed a new method of printing geometrically complex forms without the need for such support structures (Figure 7). The researchers used a six-axis industrial robot arm equipped with a plastic extruder to harness the complex and precise movements of the robot which allowed them to place material in 3D space only where it is needed for the structure to support itself. By eliminating support material in the printing process, the group increased the speed of the printing process and eliminated waste. This technology proved a more sustainable approach to manufacturing with applications in product fabrication, furniture, and architectural scale construction (Oxman et al. 2013).

MIT's research marked the rise of freeform printing projects globally. Though they pioneered the term "freeform printing", it is not a singular process but an approach to additive manufacturing. It aims to generate wholly new forms and construction processes that use robotics and borrow from AM's toolkit of materials, technology, and knowledge. Freeform printing strives to consider material spatially. But each system employs different printing strategies and techniques to define and construct their geometries, giving rise to a great variety of innovative spatial printing approaches. The projects identified in this research feature unique amalgamations of material, printing equipment, design process and desired application that, when combined, give rise to a robotic construction system unique in its capabilities. This research identifies some of the more prominent freeform printing strategies and explores how these have been applied to create novel forms and processes.

SPATIAL PRINTING MATRIX

University/ Company/Institute	Taubman College of Architecture and Urban Planning, University of Michigan	Institute for Advanced Architecture of Catalonia, Joris Laarman Studio	Mediated Matter Group, MIT Media Lab	Garamazio Kohler Research	MX3D	Hasso Plattner Institute, Cornell University	Branch Technology	Bartlett School of Architecture	Tsinghua University
Project Title	Autonomous Tectonics	Mataerial	Freeform 3D Printing: Towards a Sustainable Approach to Additive Manufacturing	Mesh Mould	MX3D Metal - Dragon Bench	WirePrint: 3D Printed Previews for Fast Prototyping	Cellular Fabrication	Spacewires - Filamentrics	Robotic 6-Axis 3D Printing
Designer/ Researcher	M. del Campo, A. Fure, W. McGee, S. Manninger, A. Flexer	P. Novikov, S. Jokic, J. Laarman	N. Oxman, J. Laucks, M. Kayser, E. Tsai, M. Firstenberg	Hack and Lauer	Joris Laarman	S. Mueller, S. Im, S. Gurevich, A. Teibrich, L. Pfisterer, F. Guimbretiere, P. Baudisch	P. Boyd IV, C. Weller, D. Wykoff, A. DiSanto, B. Hilbert, M. Rees, M. Culver, D. Fuehrer, H. Brock, J. Vereschak	N. Jiang, Y. Wang, . Chen, Z. Ahmed	L. Yu, J. Shi, X. Liu, R. Luo, Y. Cui
Date	2012	2012	2013	2012 - 2014	2014	2014	2014	2014	2014
CNC Machine	KUKA KR125/2 6-Axis Robotic Arm	ABB 6-Axis Robotic Arm	KUKA KR5 sixx R850 6-Axis Robotic Arm	ABB 6-Axis Robotic Arm	ABB Six-Axis Industrial Robot	Kossel Mini 3D Printer	KUKA 6-Axis Robotic Arm on Gantry	6-Axis Robotic Arm	KUKA R900 Six-Axis Robotic Arm
Extrusion Device	Handheld Thermoplastic Extruder Welder	Liquid Dispensing Valve	Custom Thermoplastic Extrusion Tool	Thermoplastic Extrusion Components	Standard Welding Machine	Thermoplastic Extruder	Custom Thermoplastic Extruder	Custom Thermoplastic Extruders	Custom Thermoplastic Extruder
Material	Thermoplastic	Two Component Thermosetting Polymer	HDPE	ABS	Stainless Steel	ABS	ABS w/ Carbon Fibres	ABS	ABS
Feedstock		Liquid Tube Feed	Pellets	Filament	Metal Welding Wire	Filament		3mm Filament	Filament
Extrusion Shape	Circular	Circular	Circular (Variable), Triangular, Flat, Hollow, Multi-strand	2.5mm Circular	Circular	0.7mm Circular	Star-shaped	Circular (.4, .5, .7, 1, 3, 4mm)	Circular multi-extrusion
Temperature	-	None	130C	-	-	235C	-	230 - 250C	-
Setting Device	None	Heating at tip using 2 heat guns	Various nozzle profiles for air-cooling	Compressed Air Cooling	-	Compressed Air Cooling	-	Compressed Air Cooling	Compressed Air Cooling
Speed\Time Info	-	~1m / 3mins	-	1800 x 600 x 80mm Structure / 30 hours	1-3kg per nozzle per hour	28mm^3 / 2m26s	-	100 x 220 x 80 Spaceframe / 0.5h	-
Electronic Systems	-	-	Arduino-controlled temperature, Gecko G201X Stepper Driver, NEMA 23 Stepper Motor, Heat Cartridges	"Off-shelf 3D Printing Components"	-	Solenoid for controlling compressed air	-	Arduino, Heat cartridges	Arduino MEGA, Compressed Air Solenoid, Stepper Motor Drivers
Specified Programs	-	-	Rhinoceros 5 for designing extruder	-	Autodesk Software	Custom WirePrint Algorithm	Custom C-Fab Software	FireFly Experiments	-
Printing Technique	Layering, Coiling, Pulltruding, Form-Responsive Method. Algorithmically generated toolpaths with no defined end	Freeform printing using 3D curves and self-supporting material	Freeform Printing using 3D curves and self-supporting material	Cellular banded structures with thermoplastic extruder	Wire and Arc Additive Manufacturing (WAAM)	Wireframe freeform structures with thermoplastic extruder	Cellular mesh-like voxel structures with custom thermoplastic extruders	Spaceframe and freeform structures with custom thermoplastic extruders	Multi-strand self-supporting thermoplastic extrusions mechanically emulating spider silk geometries
Adhesion Technique	Fusion Deposition	Glue Adhesion of Material	Fusion Deposition	Fusion Deposition	Fusion Deposition (Welding)	Fusion Deposition	Fusion Deposition	Fusion Deposition	Fusion Deposition
Context	Small Architectural Experiments	Small Freeform Experiments	Small Freeform Experiments	Small Architectural Experiments	Furniture Experiments	Small Design Experiments	Large Architectural Experiments	Small Architectural Experiments	Small Design Experiments
Scale	1:1 Scale	1:1 Scale	1:1 Scale	1:1 Scale	1:1 Scale	1:1 Scale	1:1 Scale	1:1 Scale	1m x 1m x 1m
Novelty	Feedback loop with a camera mounted on the robot. The camera scans previous extrusions and finds solid locations to print on, resulting in "a solid continuation of the material deposition process"	Use of thermosetting materials that can be solidified using heat at the tip of the extrusion nozzle. They can print solidified material at any point in space with any extrusion orientation.	Use of custom thermoplastic extrusion equipment with multiple extrusion pattern options that have the capacity to extrude self-supporting structures	Creation of cellular banded structures with differentiated mesh patterns for reinforcing with concrete in post-processing. These patterns are optimised for structural stability and printability.	First application of MX3D metal, creating complex 3D forms that showcases the freedom and strength of self-supporting metal structures	Use of existing 3D printing technologies with minor modifications and a custom toolpathing algorithm to create complex freeform structures.	Use of custom extrusion equipment and materials to print large architectural structures defined using their patented C-Fab software	Use of custom extrusion equipment to print complex algorithmically-defined structures and spaceframes with topologically optimised geometries	Able to print freestanding strands in space using biomimetic geometries
Associated Projects / Future Developments	Autonomous Tectonics II	MX3D Resing, MX3D Metal	-	-	MX3D Metal, MX3D Bridge	-	SHoP Pavillion, Curve Appeal, NASA Centennial Challenge	CurVoxels	-
Notes	-	-	Initial Experiments used a Stepstruder with Makerbot ABS filaments	Uses pauses to help solidify material at nodes	-	-	-	Multiple iterative developments of thermoplastic extruders	Whole extruder rotates around a central spindle and extruders oscillate mechanically. Uses FEA for structural optimisation of biomimetic structures.
Quotes	"The modelling in this case does not apply to a designer creating form, but the form created by a set of rules defined by the designer."	"This patented method allows for creating 3D objects on any given working surface independently of its inclination and smoothness, and without a need of additional support structures."	"The experiments presented in this paper provide proof-of-concept for Freeform Printing without support materials. They represent a sustainable approach to additive manufacturing and digital fabrication at large, and point towards new possible directions in sustainable manufacturing."	"The use of thermoplastic polymers, such as used in conventional 3D printers, permits precise control over the material's hardening behaviour. Pinpoint cooling during the extrusion process, for example, gives such a high level of control that free spatial extrusions become possible and, consequently, the 'knitting' of structures freely in space."	"We are developing printing strategies for different kinds of 3D-printable 'lines.' Vertical, horizontal and spiraling lines, for instance, require different settings, such as pulse time, pause-time, layer height or tool orientation."	"In this paper, we proposed a novel approach to 3D prototyping, i.e. to print wireframe representations instead of a filled model and to extrude filament directly into 3D space instead of printing layer-wise. Our validation shows that in combination, these two approaches indeed lead to a substantial speed up of up to a factor of 10 and thus allow designers to iterate more often."	"Branch Technology offers a patent pending 3D printing process called C-FAB™. This unparalleled process allows material to solidify in open space creating a cell-like matrix in virtually any shape or form. Our algorithm creates both the geometry and robotic motion to construct complex geometries in open space, without the use of support materials or highly controlled build environments."	"SpaceWires is a research project which investigated the generative methods of topological optimisation and computational methodology for structures that optimize material layout within a given design space, for a given set of loads and boundary conditions such that the resulting layout meets a prescribed set of performance targets."	"The whole process embodied the concept of 'Digital Craftsmanship', which emphasis the personality of designer and allows them to closely integrated 'Designing' and 'Fabricating'."
Potential Design Opportunities	Potential to use a similar process to respond to results of material and form experimentation. Autonomous responses to form generation integrated into the robotic system.	Precedent for an extruder that can adhere material to any surface and solidify precisely where it is placed. This would enable us to print complex 3D curves with any extrusion orientation.	Potential to create self-supporting structures using thermoplastics by building custom extrusion equipment that can be adapted to suit material needs	Precisely cooling the extrusions could enable our project to precisely place material in space, liberating the forms that the system can produce	Potential to adapt similar computational strategies and enable self-supporting structures by implementing control over robotics and extruder variables	Potential to print complex freeform structures through precise control over the 3D printing constraints with custom toolpath generation that accounts for a material's response to the system.	Potential to use a similar structural approach to building forms, and investigation of materials and extrusion shapes for selfSupporting structures	Potential to integrate topological optimisation tools into design process and toolpath construction. Also has extruder development precedents for my research	This project has extensive documentation of the robotic system and extruder design process and has a unique approach to creating self-supporting structures that could inform the toolpath design process for this project
Potential Improvements	Could respond to material experiments by focusing on improving craft qualities of the material and process.	Could experiment with more complex 3D forms and automated printing strategies	Expansion of materials used in project. "... further development of active heating and cooling at the tooltip, allowing for greater freedom of possible print geometries"	Exploration of more complex curved forms	Exploration of more flexible computational methods of defining forms	"For future work, we plan to explore how fast 3D printing allows for novel types of interfaces that close the feedback loop between digital editing and physical fabrication."	Exploration of more flexible computational methods of defining forms	Greater focus on integration of computational tools into robotic processes to improve material responses	Opportunity to create novel structures using these self-supporting strands

Bartlett School of Architecture	Disney Studio, RMIT University	Gramazio Kohler Research, ETH Zurich	MIT	Festo	Ai Build	Architectural Association School of Architecture Design Research Laboratory	MIT Self-Assembly Lab, Christophe Guberan, Steelcase	Nagami, UCL Design Computation Lab	MX3D
CurVoxels	Hybrid Phantasm	Extruded Structures / Iridescence Print	Robotics-Enabled Stress Line Additive Manufacturing	3D Cocooner	Affordable Large Scale 3D Printing	LOCI	Rapid Liquid Printing	Voxel Chair V1.0	MX3D Bridge
H. Kwon, A. Kaleel, X. Li		A. Thoma, L. Piskorec, A. Gandia, N. Hack, D. Jenny, P. Lindstrom, A. Mirjan, J. Yeao, A. Szabo, B. Cheng, T. van der Lely, A. Cecile, L. te Loo, E. Herrera, N. Ganz, P. Ruckstuhl,	K. Tam, J. Coleman, N. Fine, C. Mueller	W. Stoll, H. Frontzek, E. Knubben, S. Henrich, S. Droste, R. Spycher, D. Jentsch, K. Willius, N. Gaissert	D. Cam, M. Desyllas, D. McKaigue, L. Leonidou, Z. Li, I. Asimaki, A. Hidalgo	A. Bhosle, L. Semenyshyn, R. Omar, S Bhooshan, T. Spyropoulos	K. Hajash, B. Sparrman, M. Koh, S. Kernizan, J. Laucks, S. Tibbits, C. Cuberan, Y. Hiyoshi, M. McKenna, P. Noll, S. Tracy, E. Bilt, C. Norman, C. Forslund	M. Garcia, M. Angel, J. Garcia, I. Ochoa, G. Retsin, V. Soler, M. Jimenez	J. Laarman
2014-2015	2015	2015	2016	2016	2016	2016	2017	2017	2015-2018
6-Axis Robotic Arm	KUKA KR150 6-Axis Robotic Arm	Universal Robot UR5 Robotic Arm	KUKA KR6 R900 6-Axis Robotic Arm	Festo EXPT-45 Tripod Kinematic Robot	KUKA 6-Axis Robotic Arm	ABB IRB6640 Robotic Arm	Robotic Arm	Six-Axis Robotic Arm	ABB Six-Axis Robotic Arm
Customised Thermoplastic Extruders	ExOn 8 Thermoplastic Extruder Welder	Custom Thermoplastic Extruder	Custom Thermoplastic Extruder	Festo Resin and Fiber Extruder	AiMaker Extruder	Custom Thermoplastic Extruders	Custom Paste Extruder	Handheld Plastic Extruder Welder	Standard Welding Machine
ABS	PLA, HDPE, PP	ABS	PLA	Glass fibre thread & UV Curing Resin	ABS, PLA	UV Cured Resin, Clay, Axon EasyMax, PLA mostly	2 component polymers incl. plastics, rubbers, and polyurethanes	PLA with blue tint	Weldable Metal Alloys (incl. Stainless Steel, Steel, Aluminium, Bronze, Inconel)
3mm Filament	Pellets	Filament	1.75mm Filament	Resin and Fiber	Filament	Filament	Paste	Pellets	Metal Welding Wire
4mm Circular	Circular	2 - 3mm Circular	Circular	Circular	Circular	3mm Circular, Multi-extrusion	Circular	Circular	Circular
-	-	210C	-	-	-	180 - 200C	-	-	-
Compressed Air Cooling @ 100kg/cm^2	None	Compressed Air Cooling	-	365nm 9.3mW fibre-coupled UV Lasers	-	None	-	Compressed Air Cooling	-
18mm/s	-	-	-	10mm/s	-	30mm/s	-	-	1-3kg per nozzle per hour
Arduino, Heat Cartridges, NEMA 17 Stepper Motor	None	-	Arduino Uno, MOSFET, Thermistor, Stepper Motor, Heater Cartridge, EasyDriver Stepper Driver	-	-	24V Arduino, Stepper Motor Drivers, Heater Cartridges	-	-	-
-	Rhinoceros 5, Grasshopper	-	Custom Stress-Line Additive Manufacturing (SLAM) Software	Custom Festo Control Software	AiBuild - Custom cloud-based control software	-	-	-	Autodesk Software
Voxel-based freeform structures using custom thermoplastic extruders	Layered structures using industrial extrusion equipment	Spaceframe structures using custom thermoplastic extrusion equipment	Structurally optimised 2.5D surfaces printed using custom robotic extrusion system	UV-Curing resin with a fiber core printed under tension	Multi-process spaceframes and architectural models printed with custom software and extruder	Multistrand coiling extrusion under tension	Two-component polymer suspension in gel medium	Thermoplastic freeform extrusion using voxel patterning	Wire and Arc Additive Manufacturing (WAAM)
Fusion Deposition	Fusion Deposition	Fusion Deposition	Fusion Deposition	Resin Adhesion	Fusion Deposition	Fusion Deposition	Polymer Adhesion	Fusion Deposition	Metal Welding
Small Architectural Experiments	Small Architectural Experiments	Small Architectural Experiments	Small Surface Experiments	Small Design Experiments	Large Design and Architecture Experiments	Small Design Experiments	Small Design Experiments	Full-size Design Experiments	Furniture and Architectural Structures
1:1 Scale	1:1 Scale	1:10 Scale, 1:1 Scale	150 x 150 x 60mm	450 x 300 x 600mm	3.2m x 3.2m x 2.8m Max	3m x 3m Robotic Reach	Limited by size of gel vat	1:1 Furniture	"Virtually Unlimited"
Use of custom extrusion equipment to print geometrically adaptable structures defined using voxel systems	Use of industrial extrusion equipment to print large-scale architectural experiments using freeform techniques	Use of custom extrusion equipment to print large multi-coloured spaceframe structures	Custom design of a robotic fabrication system to print 2.5D structurally optimised surfaces	Custom robotic process for spatially printing UV curing resin with a fiber core	Fully autonomous freeform 3D printing from anywhere in the world using proprietary printing techniques and equipment	Multistrand extrusion under tension techniques using FEA analysis and physical experimentation for compressive structures	Negation of deflection due to gravity through use of a gel suspension medium	Use of a compressed air system with a plastic extruder welder to create freeform structures defined by voxel patterning techniques	Able to print a large variety of metal alloys in virtually any shape and size
Spacewires / Filamentrics	-	-	-	-	Daedelus Pavillion, Thallus	-	-	-	Gradient Screen, Cucuyo, Butterfly Screen, Dragon Bench
Multiple iterative developments of thermoplastic extruder, multi-extrusion nozzles. Node pause time of 3 seconds	Hints at using a 3D scanner as a feedback mechanism for the material's response to the system. Pellets change colour throughout print	Continuous extrusions, multicoloured across the entire model by using different coloured pellets	24V robot signal controls extruder on/off. Uses Arduino-controlled closed-loop PWN temperature control, and extruder uses retractions	Interesting chair design in brochure	Intention on full automation of manufacture integrated with AI systems. Feedback loop on material performance with integrated camera system	Development of a scanning end effector for measuring material response to the robotic process	Interesting furniture output for project - Steelcase table	Full size furniture output for project	MX3D Bridge is a full-scale end-use architectural project that is still under construction at the time of writing
"This research aims to focus on a new digital design architectural methodology and also a new fabrication realization methodology. Basically this research is significant in that is suggests a new aesthetic and structural paradigm for architecture and also for providing the actual foundation for the possibility of its commercialization."	"In contrast to system such as concrete casting, vacuum forming, or robo-molding, which utilize a formwork in order to give a system a specific shape the project relies on a set of rules that trigger a behaviour in the robotic system in order to erect spatial figurations, capable of creating emergent behavious within a system of material aggregation."	"Iridescence Print is the first large-scale architectural installation to be automatically printed by robotic machines. Conceived as a spatially complex lightweight structure, the installation synthesizes a rigorous exploration of the architectural potentials of robotic extrusion of spatial meshes at full architectural scale."	"The most important contribution is the demonstration of a new consolidated methodology encompassing parametric design, form-finding, structural optimization, robotic computation and digital fabrication, which uses robotic-integration to achieve a structurally-informed method of fabrication that provides designers with an opportunity to explore a fuller design space that considers both geometry and performance."	"For the 3D Cocooner, the developers equipped a tripod from the standard Festo range with a special nozzle. With the help of UV-curing resin, it spins a soft glass-fibre thread into complex and equally stable shapes that are very similar to the natural structures. The kinematics receive the necessary control commands directly from the design program in which the three-dimensional shape model is generated."	"We are on a mission to enable factories of the future with Artificial Intelligence. A future where manufacturing is easy, smart, sustainable and affordable."	"The studio research agenda explores the use of combine technologies, robotic arms and 3d printing, in the architectural design process. The main objective is to translate structurally motivated spatial networks into habitable dwellings. This can only be achieved by integrating digital fabrication into the design and production process."	"Rapid Liquid Printing physically draws in 3D space within a gel suspension, and enables the creation of large scale, customized products made of real-world materials. Compared with other techniques we believe this is the first development to combine industrial materials with extremely fast print speeds in a precisely controlled process to yield large-scale products."	-	" In our vision, MX3D Robots will build lightweight constructions like bridges or complete buildings, optimized custom ships or even Mars colonies in full autonomy"
Possibility of using a voxel-based system for generating and organising printing geometries. Also has extruder development and multi-nozzle experimentation precedents	Potential to use industrial extrusion equipment and a similar design process as part of our freeform system	Potential to use similar extrusion and cooling systems and generate large architectural spaceframe structures	This research has useful precedents for building a robotic fabrication system, and demonstrates how that system can be integrated with structural information	This product employs design strategies to print with coextruded polymers which could be useful for this research	This company demonstrates an effective solution to spatial freeform printing with thermoplastics, and sets a good precedent for this project for designing a robotic fabrication system and responding to material performance within the fabrication sytem	This project sets a precedent for this type of design research, with documentation of multiple extruder developments, design approaches, materials experiments and physical testing.	This project has an interesting approach to supporting spatially printed materials and this lateral thinking towards solving this problem could help in my project	This project created a full-size furniture piece that was strong enough to support a human. Similar outputs could be considered for this project	MX3D has created a robust and capable freeform printing system sets a precedent for the types of structures that out system can hope to emulate
Greater focus on integration of computational tools into robotic processes to improve material responses	Improved control over extrusion equipment, addition of cooling, and a greater focus on material responses to the system	Exploration of more flexible computational methods of defining forms	Exploration of freeform outputs of this system and how this level of robotic control can be used to improve self-supporting capabilites of the printed structures	Could be useful to implement a fiber separation mechanism for non-continuous printing	Would be interesting to test a range of different toolpath design approaches	Possible to develop extruder into a tool that can produce more high-resolution outputs	Could be possible to investigate into different thermoplastic materials and high-temperature gel-mediums	Opportunities to use this extruder to output higher resolution geometries with greater focus on material responses	Opportunities to experiment with different types of structures and materials

Figure 10: Spacewires (Bartlett School of Architecture, 2013)

Figure 11: Flotsam & Jetsam Pavillion (SHoP Architects, 2016)

Figure 12: Dragons Bench (Laarman, 2014)

PRINTING TECHNIQUES

Most freeform projects learnt from Fused Filament Fabrication (FFF), adapting FFF equipment and toolpath generation to build geometries unilaterally across X, Y, and Z axes. Like the slicing method used in FFF, print models are segmented into bands that are layered vertically and printed consecutively from the ground upwards. These printable bands are generated ground-up programmatically or calculated top-down from a final intended form, but all consist of a repeating set of preconfigured toolpaths that are optimised for printing spatially.

This type of approach is particularly suitable for building spaceframe structures such as those projects by Gramazzio Kohler Research, AiBuild, and Branch Technology. Splitting up larger geometries into bands and segmenting those bands into units or "cells" allows for the geometries to be built up piecemeal - much like bricks in a brick wall. In this way, the toolpath and print settings for the parent cell can optimise the project-specific material and equipment configurations and subsequently pattern the entire print model. The advantage is that the mechanical properties and printability of the whole model can be extrapolated from one parent cell. This enables low-resolution geometries that employ thermoplastic extruders that maximise support structures from the cell walls and adjacent cells.

Projects such as CurVoxels and Branch Technology have created a more adaptable and geometrically complex spatial printing system by using voxels to define and organise their digital models. Much like the cellular patterning described above, CurVoxels breaks up geometries into 'spatial voxels' that are patterned into the output print geometries - but the internal structures of the voxels vary in density and geometry to reflect the relationship between each connected voxel and the structural requirements of the overall object. This method relies on fully integrating complex computational tools but opens up possibilities of incorporating related computational processes. An example is their Finite Element Analysis (FEA) system that provides a feedback loop of structural information into the modelling system (Bartlett School of Architecture, 2014).

Branch Technology has employed a similar approach with their Cellular Fabrication (C-FAB) process in which the geometry of each cell in the model adapts to the intended overall shape allowing them to "create a cell-like matrix in virtually any shape or form" as demonstrated in their Flotsam & Jetsam pavilion designed by SHoP Architects (Figure 11). Spaceframes such as these are of interest to the architectural community for their ability to bear structural loads, post-processed with insulative foam and cladding into finished walls with complex curvatures (Branch Technology, 2017).

Another approach to spatial printing uses complex 3D curves and surfaces as drivers for the printing toolpaths resulting in higher resolution structures with more design freedom. Liberating form like this necessitates an increased focus on material support, and many projects have sought to maximise the self-supporting capabilities of their systems to print increasingly complex structures.

Lei Yu created a robotic system with a multi-nozzle thermoplastic extruder that extruded self supporting material strands in space by mechanically mimicking the geometric structure of spider silk threads. Yu printed these strands between already-fixed structural points like a spider would spin a web (Yu, Shi, Liu, Luo, & Cui, 2015). Printing strands without those supports must use a more structured approach such as with Joris Laarman's Dragon Bench (Figure 12). Laarman experimented with creating self-supporting structures using heat-setting resin and MIG welded metals at his company MX3D. He created a large metal furniture piece by printing a 3D mesh that expanded and contracted around a complex twisting computational form. Printing a structure like this requires complete control over settings like pulse-time, pause-time, layer height and tool orientation that change depending on the orientation of the lines in space (Laarman, 2014)(MX3D, 2018). Gaining this level of control to attempt more complex geometries with greater design freedom is key to realising the aims of this research.

"3D printing like this is still unexplored territory and leads to a new form language that is not bound by additive layers."– Joris Laarman

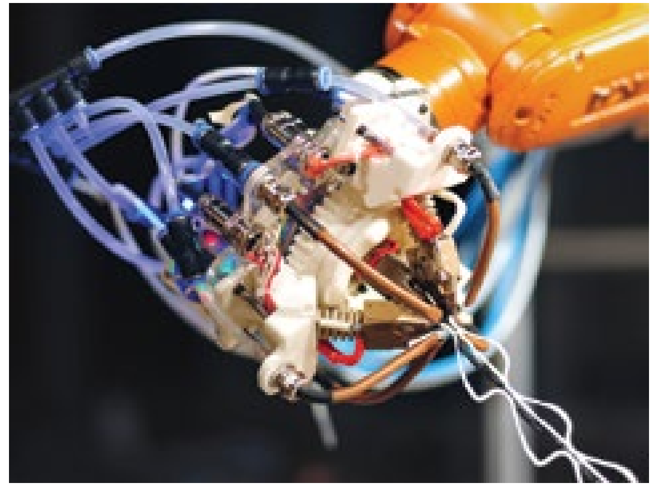


Figure 13: Robotic Extrusion (Lei et al., 2015)

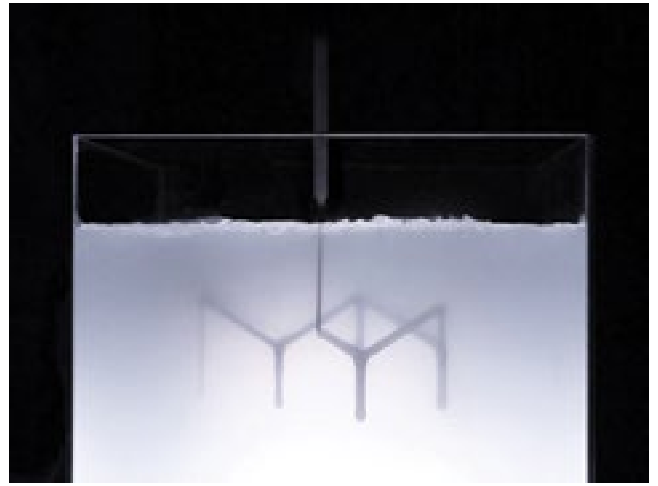


Figure 14: Rapid Liquid Printing (Tibbits et al., 2017)

Figure 15: ICD/IDKE Pavillion (Institute for Computational Design and Construction, 2015)

FREEFORM PRINTING EQUIPMENT

The majority of freeform printing projects identified in the spatial printing matrix used 6-axis industrial robot arms as their movement base to enable the freedom of extruding material anywhere in space at any orientation. However, for a spatial print to succeed it must navigate the middle-grounds between this freedom of complexity and the response of their material to the digital model, printing process, and structural imperatives that comprise their intended forms. Each project investigated in this research is unique in its combination of material, extrusion system and programming, and each has its process-specific applications and printing parameters. By investigating the technical capabilities of each freeform system as an inductive driver for these applications and parameters, it is possible to glean the critical provisions of their successes. As such, this section investigates the various approaches used to enable the printing of freeform structures with minimal supports.

The critical necessity for every project achieving freeform structures is the ability to solidify the print material so that it maintains its position in space with minimal deflection. In the case of spatial systems using thermoplastic extruders, the extrudate must be quickly set leaving the plastic minimal time to droop or deform once it's outside of the extrusion nozzle. For example, Spacewires (Bartlett School of Architecture, 2013) and 6-Axis Robotic Extrusion use compressed air to cool the plastic at the tip of the nozzle (Figure 13), and Branch Technology use a star-shaped extrusion that cools faster as a result of the increased surface area (Branch Technology, 2017). LOCI removed the nozzles from their extruder so that the material can flow straight through it passing only long enough to make the material flexible but not liquid so that it is already mostly solidified (Bhosie et al., 2016).

Rapidly cooling the material can reduce the dependency on support structures, but other projects demonstrate further methods of supporting the material in space. Mesh-Mold prints onto a robotic surface that reorientates itself so that the nozzle always points downwards and prints strands vertically on top of already printed geometries. The effect of gravity pulling the molten plastic onto the already cooled plastic uses the strand itself as support. Other processes such as Rapid Liquid Prototyping negate the effects of gravity altogether by suspending liquid material within a gel medium until it sets, and the ICD\IDKE 2014-15 Research Pavillion was made by adhering extrusions to the inside of an inflated build envelope which simultaneously acts as the building's exterior skin.

By considering the successes of those projects with active cooling systems and combining this with techniques that either provide support for freeform extrusions or remove the need for them entirely, there is potential to create a spatial printing system that maximises the opportunities for spatial experimentation. Creating a system that can specifically address the technical requirements of the materials through explicit control of the robotic system and extrusion equipment opens up a space for in-depth experimentation into the relationship between materials and spatial printing processes.

Figure 16: Mataerial (Laarman, Novikov, Jokic, 2013)

Figure 17: WirePrint (Mueller et al., 2014)

Figure 18: Daedalus Pavillion (Cam et al., 2018)

The first critical factor identified in the previous section was the physical placement of material. Once the equipment configuration is capable of placing solid material at any point in space, the next critical factor is programming the toolpaths for the robot and extruder. Freeform printing is effectively a direct translation of movement into form - as the robot moves to each target in space, it leaves a trail of material like a solid afterimage until a shape emerges; the toolpath becomes the object. So there are many design opportunities in computational design environments to define toolpaths and the level to which the robot and extruder can interpret information from those environments.

A robot's movements are only as complex as its programming, and in its simplest form the instructions sent to the robot are a list of points in space to move to with conditions on how to move there. Draw a line through all of these points from start to finish, and the result is a toolpath that the tool attached to the robot will follow. A toolpath can be generated in a plethora of different ways; Mataerial used the points from NURBS curves written in Rhinoceros to print their resin experiments (Figure 16), and WirePrint turned the wireframe preview of some simple solid objects into toolpaths for an FFF 3D printer (Figure 17). In FFF printing each toolpath has associated extrusion values which instruct the tool when to extrude material and at what rate; Slicing programs assign an extrusion and feedrate value to each extrusion movement that changes depending on the printer's speed and predefined slicing parameters. Much like an FFF machine, an industrial robot takes instruction from a list of commands in its proprietary code. However, it is unclear from the literature whether this level of control between extrusion and movement has yet been achieved by the freeform projects identified in this research.

Larger and more complex geometries translate into longer machine code that is often too laborious to program manually. Many of these freeform projects overcome this by algorithmically interpreting the geometries of their prints into hierarchical segments much like the slicing and layering method used in their FFF precedents. Projects such as Mesh-Mould (Hack & Lauer, 2014) and AiBuild (Cam et al., 2018) take the intended final form of their model and algorithmically populate the envelope of this form with a pattern of preset freeform toolpaths that adapt to the shape of their input geometries, such as the Daedalus Pavillion shown in Figure 18. Algorithmically calculating the toolpaths introduces some significant benefits: generating larger structures is quicker and less labour intensive, the behaviour of the algorithm that generates the robot's toolpaths can be programmed holistically across the model, and the processes governing the toolpath can assign its corresponding extrusion parameters as part of the same process. This offers the ability for the forms to be updated frequently by quickly and automatically generating the necessary toolpaths and machine code to print them.

Automating the printing process in this way standardises the inputs and outputs of the freeform system allowing for a level of systematic control in experimentation. Furthermore, a material's response to the parameters of the freeform printing process can be characterised by directly comparing the fidelity of the output to the toolpath that it was placed along. These capabilities form the basis of a feedback loop between the input parameters and the output model that enables the design process to be informed by the observed design qualities and mechanical performance of the material. The input parameters can then be optimised to achieve the desired properties which in turn can be measured directly from the output model, effectively coding the material response into the manufacturing process. Because the relationship between materials, structure and process can be quantified it can thus be factored into the definition of the system, enabling an experimental approach to improve that system based on empirical testing and results. This situates spatial printing as a reflexive system at the heart of a web of interlinked physical, robotic and computational processes, bringing it closer to the realm of programmable material.

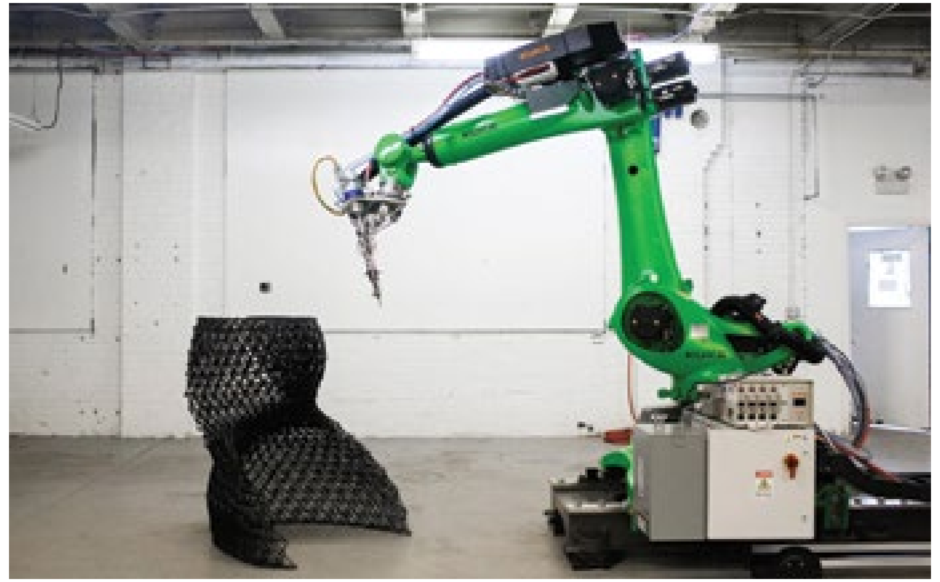


Figure 19: Branch Technology (Branch Technology, 2017)

Figure 20: Spacewires (Bartlett School of Architecture, 2013)

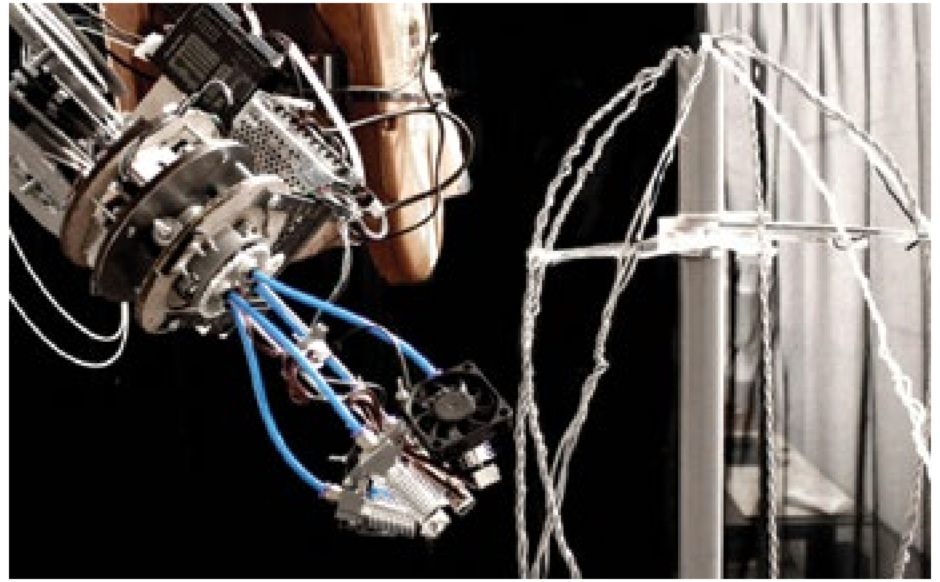


Figure 21: LOCI (AADRL, 2016)

Figure 22: Robotic Extrusion (Yu et al., 2015)

PRIMARY PRECEDENTS

BRANCH TECHNOLOGY

Branch Technology specialises in using freeform 3D printing to create large architectural structures. They use their specially developed Cellular Fabrication (C-Fab) technology. They can build complex freestanding structures by layering unit cells that can be freeform 3D printed into a mesh-like matrix, such as the Flotsam and Jetsam Pavillion designed by SHoP Architects (Branch Technology, 2017). The company have since won NASA's 3D Habitat Challenge by printing architectural components for extraterrestrial habitats, and is currently building the world's first freeform printed house "Curve Appeal" (Figure 19)

SPACEWIRES / CURVOXELS

Bartlett School of Architecture in the UK have researched freeform printing using a variety of techniques in their research portfolios; printing spaceframes and complex hierarchical structures in Spacewires-Filamentrics using a voxel-based toolpath generator for printing full-scale furniture models. Their researchers also created a "design-fabrication integration system" that accounts for the freeform manufacturing constraints as a part of the design process (Figure 20).

LOCI

LOCI is the research booklet for the Master of Architecture students at the Architectural Association School of Architecture Design Research Laboratory in the UK. The main objective of the project was to translate structurally motivated spatial networks into habitable dwellings and explore the combination of robotic arms and 3D printing in the architectural process. The group experimented with multiple methods of freeform printing, explored structural and tensile freeform printed structures, and used computational methods to simulate material performance and the printing process. (Figure 21)

ROBOTIC EXTRUSION (6-AXIS 3D PRINTING)

Lei Yu at Tsinghua University created a robotic fabrication system that extruded strands of plastic mimicking the structures of silk spider webs found in nature. By simulating potential extrusion patterns using their material properties, Yu was able to optimise for patterns that could account for the deflections of the extrusions due to gravity. He then designed an extruder with multiple heads that mechanically moved through a set range of motion resulting in a unique extrusion profile with self-supporting properties, and his research team printed these in free space using a 6-axis robotic arm (Figure 22).

OVERVIEWS

OVERVIEW - ROBOT

Figure 23: Author, VUW Industrial Robot Arm

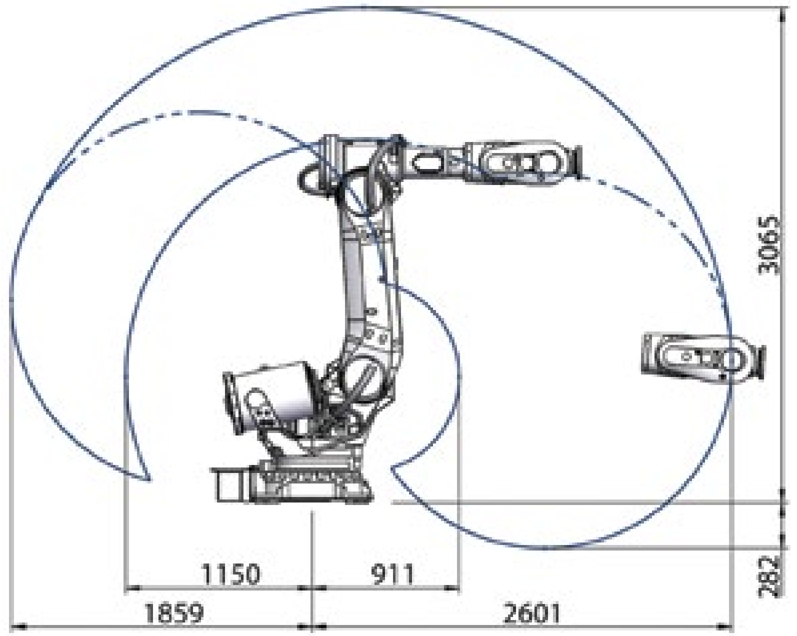


Figure 24: IRB6700 Reach Map (ABB, 2017)

This project will employ Victoria University's industrial robot arm located at the Te Aro Campus on Vivian Street. The robot will serve as the CNC base for all of the freeform printing experiments and as such the specifications of this robot will dictate the requirements of the thermoplastic extruder to be built for it as well as the design process for the freeform printing it will facilitate.

The robot is an ABB IRB6700-200 6-Axis Industrial Robot Arm with a 200kg payload and a 2.6m reach. It is programmed using proprietary RAPID code, has a positional repeatability of 0.06mm and a path repeatability of 0.08mm which is precise enough for the tolerances of the freeform printing process. The working range, or "robotic cell," is shown in the image opposite. Accounting for the geometry of the extrusion tool, this robotic cell governs the size of the objects that the freeform system can make.

The extruder built for this project will need to attach to one of the robot's physical interfaces. There are two possible connection points that can be used; the university's robot is equipped with a SCHUNK tool changing system and electrical modules, and FESTO pneumatic grippers. The grippers have been fitted with custom jaws that allow the robot to clamp on to the cylindrical base of different tools that were used in a previous robotics project. These tools have a tool changer mounted in the robot's reach that allow them to be swapped out autonomously if multiple tools need to be used in a single process.

The control cabinet of the robot has been fitted with two communication modules that can be assigned functions additional to the robot's standard programming. One of these is a digital input/output module that can both send and receive 24VDC signals. This module can be used to instruct a process to turn on or off or receive instructions that a process has reached a certain target. The second is an analog signal output module that allows the user to send precise voltages between 0-10VDC to a designated input; this module can be used to specify parameters on-the-fly as a part of the robot's movements.

OVERVIEW - MANUFACTURING RESOURCES

As the nature of this research is experimental, building a system capable of spatial printing required parts that were not commercially available. Much of the equipment outlined in this research has been custom made for this project unless otherwise stated. The manufacturing resources used to build these spatial printing systems include those illustrated below, as well as a range of standard workshop tools and electronic components.

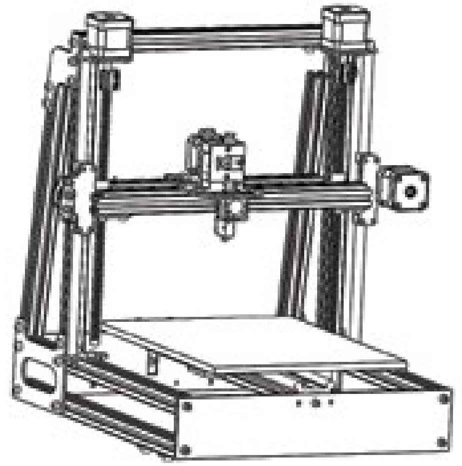


Figure 25: Author, MendelMax 2.0 3D Printer

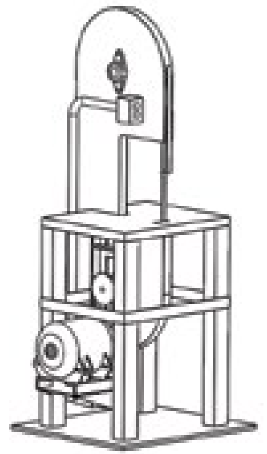


Figure 26: Author, Band Saw

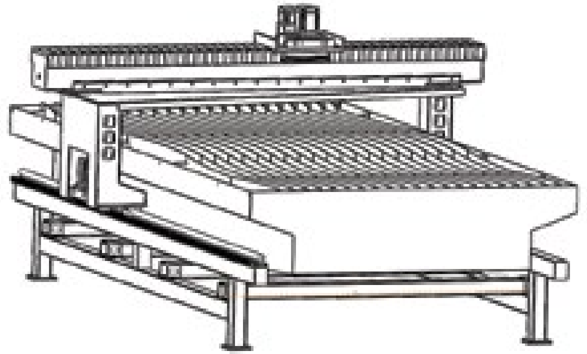


Figure 27: Author, CNC Plasma Cutter

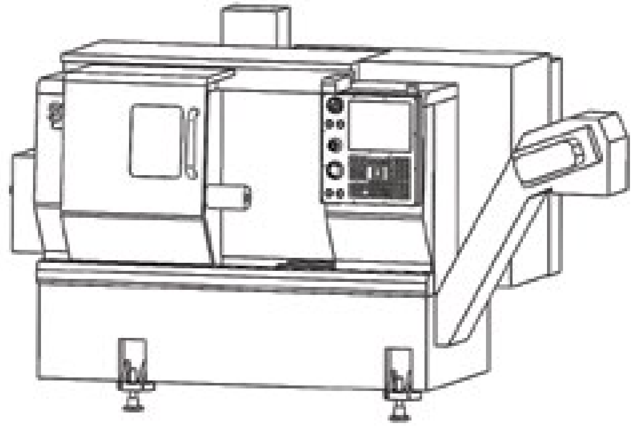


Figure 28: Author, CNC Lathe

Figure 29: Author, Pillar Drill

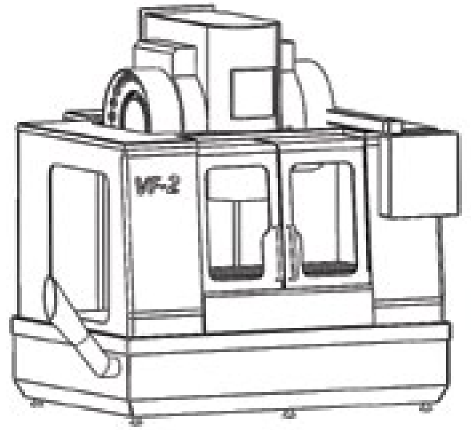


Figure 30: Author, CNC Mill

Figure 31: Author, Scion Co-extrusion Filaments

Figure 32: ProHT Biopolymer Filament (BigRep,2018)

The materials that our research partner is providing for these experiments are biopolymer thermoplastic filaments co-extruded with natural fibers at their core. These filaments are custom made for this project and use polymers made from New Zealand timbers. Our partner has produced a range of filaments that consist of combinations of ecologically-sourced protein and PLA polymers each with a variant of natural fiber at its core such as wool, flax, or protein strands.

Our research partner is aiming to make their filament materials in the standard sizes for FDM printing, 1.75mm and 3.00mm. This allows us the opportunity to use the wealth of FDM filaments on the market to initiate the preform project as a precursor to testing with their materials. The filaments I will use are selected for their estimated capacity for spatial printing and their similarity to the custom materials.

Ultimately the successes of this spatial printing system rely on its ability to adapt to a material's response to the printing process by using the results of experimentation to inform changes in that printing process. Given that one of the primary focuses of this research is to investigate the craft qualities of New Zealand biopolymers, the materials selected for these experiments will pursue that goal to the extent that they are able. In the absence of desirable spatial printing qualities, materials that respond well to the printing process will be used to refine that process until it enables the printability of biopolymers with improved craft qualities.

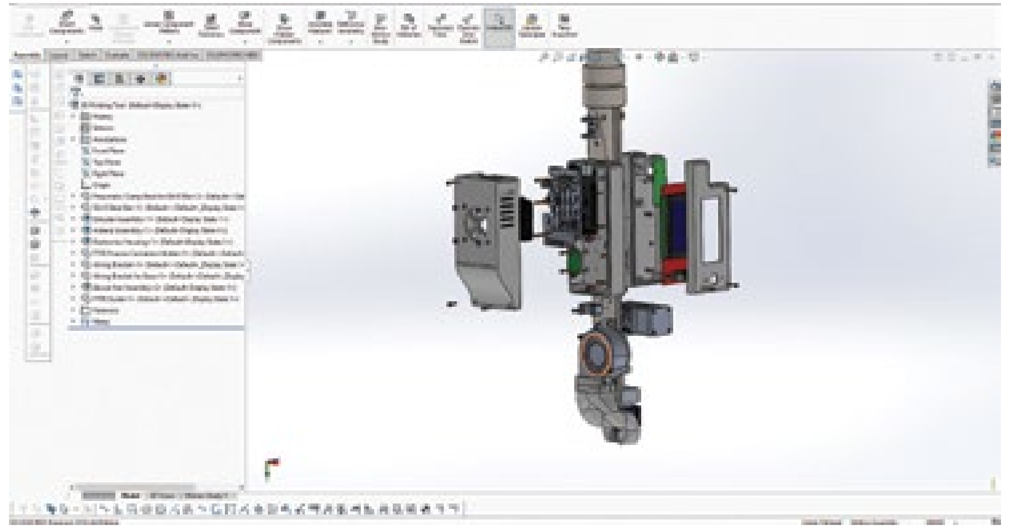


Figure 33: Author, Solidworks Design Environment

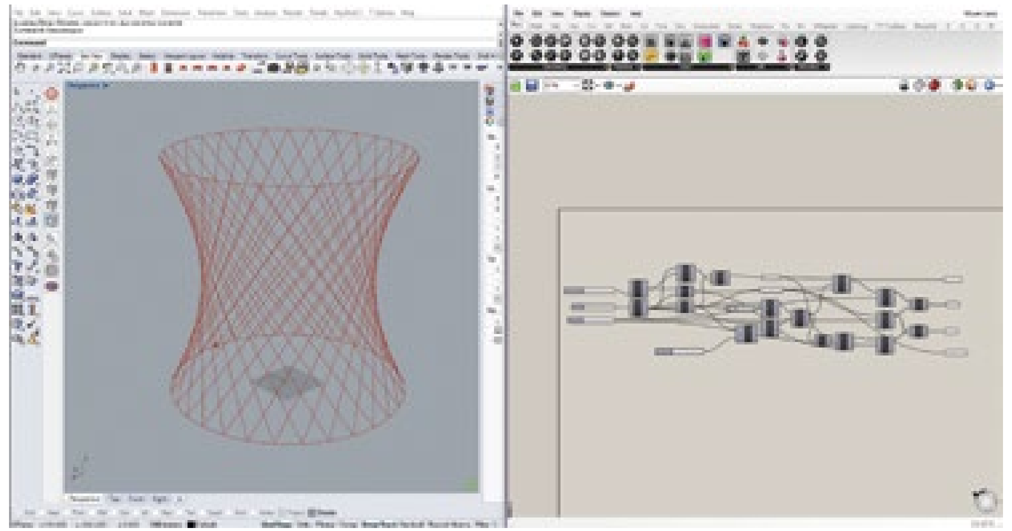


Figure 34: Author, Rhino & Grasshopper Design Environment

The first part of this project will involve building an extruder for the industrial robot arm which will require creating assemblies of existing componentry and bespoke parts that are to be manufactured using the processes on the previous page. The School of Design has access to SolidWorks by Dassault Systèmes which is capable of both importing CAD data in most standard formats for the robot and other existing components and exporting the CAD data and technical drawings for part manufacture. SolidWorks will be used throughout this project for manufacturing all the custom components for the robot arm.

Rhinoceros and Grasshopper will be used as the design software for generating the freeform structures and toolpaths to be printed by the robotic system. Rhinoceros uses NURBS modelling to produce mathematically precise representations of curves and freeform surfaces (Wikipedia), and Grasshopper is a plugin for Rhinoceros that offers parametrised control over those curves and surfaces.

Grasshopper has a plethora of plugins that are useful for this project including HAL Robotics and Firefly Experiments. HAL offers explicit control over all of the robot's functions and translates the geometries from Grasshopper into processes and movements in a language that the robot can understand. Firefly Experiments enables live communication with Arduino microcontrollers and can provide a method of communicating and orchestrating extruder and robot movements. The combination of these software packages has the capability of fully automating the freeform printing process whilst remaining entirely adaptable and responsive to the results of experimentation.

RESEARCH METHODS

RESEARCH QUESTION

What design qualities can be achieved with New Zealand biopolymers and how can we realise these qualities using spatial 3D printing?

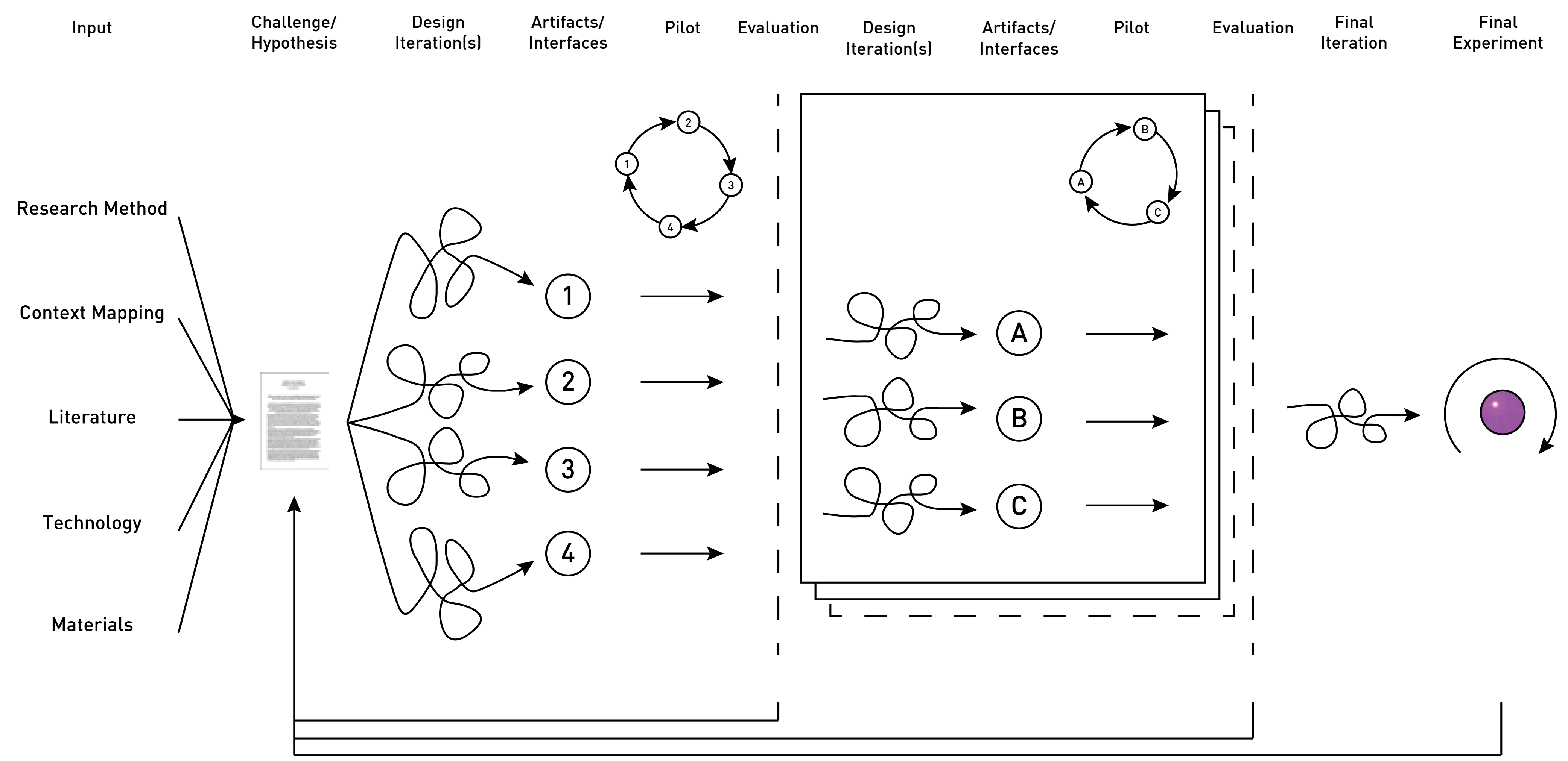


Figure 34: Empirical Research Through Design Method (Keyson & Bruns, 2009)

Aim 1: Design, build, and implement a freeform manufacturing system capable of generating large-scale artefacts with desirable design qualities

Ultimately, the objective of this project is to create a robotic 3D printing system that can enable research into large-scale, geometrically complex freeform structures. The further aims of this project rely on a fully functional spatial printing system so achieving this primary objective is of paramount importance to both this research and the other freeform projects based on this research. To this end, exemplary freeform projects and related additive manufacturing research were identified, analysed, and discussed with a specific focus on the technical composition of each manufacturing system such as their robotic platform, extruder construction, controller programming, and design environment. This investigation found a large variety of approaches to constructing spatial printing systems with significantly different equipment, construction materials, and applications. Navigating this field holistically as demonstrated with the freeform printing matrix is critical to understanding the underpinning innovations that enable spatial printing, especially since much of the technical information needed to create such a system is not available in any of the investigated research documentation. This project will thus draw from an existing pool of FDM knowledge and technologies using an approach similar to those applied in the primary precedents, and draws inspiration from all of the information gleaned from the background research to build a spatial printing system with the greatest possible freedom of complexity.

Aim 2: Iteratively test and improve the system in response to desirable craft qualities using Scion's biopolymer materials

A large portion of this research will involve experimentally testing this spatial printing system using an array of design models that are designed to focus on specific aspects of the spatial printing process to improve the system. This process will be repeated using a variety of materials including biopolymer and co-extrusion filaments that are custom-made for this project by our research partner. Given the large experimental focus and interdisciplinary approach, this research will follow the Empirical Research Through Design Method (ERDM) (Keyson & Bruns, 2009) that will use a mixed methods approach incorporating elements of materials experimentation and prototyping. The ERDM (shown opposite) states that "The key aspect of ERDM is to create experimental variability in the product prototype so as to formally test the underlying theoretical design questions at hand and in a real-world context. The variability of prototype variability has to be carefully defined so as not to confound the research question at hand"(Keyson & Bruns, 2009). This statement is especially true considering the multiple foci of this research, as most of the challenges with interdisciplinary research are related to divergent methods and methodologies (G. Muratovski, 2016). The ERDM lends itself as the most suitable framework for this research as it allows for the iterative development of multiple design scenarios from which important findings can be fed into following iterations to improve the artefacts or interfaces (Keyson & Bruns, 2009). Each iteration of extruder, material, or model can be reviewed relative to each other and in direct response to the overall research objectives.

Aim 3: Investigate unique and large-scale applications of the freeform system from an industrial design perspective

As the advent of spatial printing in this way is relatively recent, much of the technical and design aspects of existing freeform systems are still in development. Investigation into the broadening possibilities that complete control over a flexible spatial printing system presents opens up opportunities for designing novel artefacts and processes that harness the strengths and design qualities of the system as induced by the results of experimentation. With the successful manufacture of large-scale design artefacts, a space for further design research is defined that can focus on improving this system, integration of spatial printing into multi-process robotic manufacture, and creating new forms that are unique to the system as a whole.

Figure 35: Author, Research Development Diagram

RESEARCH DEVELOPMENT DIAGRAM

Over the course of experimentation, the spatial printing system will be iteratively improved by testing each new addition to the system piecemeal. The successful additions will be integrated into the system as a constant for further experiments and will be catalogued using the modified Venn diagram shown opposite. This diagram represents the interactions between the three fundamental components of the spatial printing system:

EQUIPMENT & HARDWARE

Physical equipment comprised of all the extruder hardware, robotic systems, and associated cabling and connectors

SOFTWARE & CODING

Coded systems to interpret design models into robotic processes. Includes Grasshopper list operations, RAPID code generation, and Arduino firmware

DESIGN SOLUTIONS

Systems within the design model that adjust and interpret the input geometries to account for the materials response to the system

The overlapping sections demarcate developments in the system that form a connection between each of these components. For example, a **PURPLE** tile represents a connection between the robot control cabinet's programming and the extruder hardware. Progress is each section is represented by a chevron that progresses outwards in the order of integration but does not necessarily indicate that the components are merged together.

The process of printing a model spatially using this system can be emulated by reading the diagram clockwise from the top. A simplified version of the system would progress as follows: A design input is fed into the spatial printing system where it is interpreted into a list of robot and extruder commands that are uploaded to the robot control cabinet which instruct the robot arm to perform the programmed movements. A fully integrated spatial printing system requires a connection between each adjacent component, creating a feedback loop that is used to iteratively test and respond to the needs of the system. This is represented by a diagram with a minimum of one of each colour tile so that the cycle can run continuously


EXPERIMENTS I

SPATIAL PRINTING SYSTEM

BUILDING A FREEFORM SYSTEM - CORE DECISIONS

Like a majority of other freeform printing projects, this process will be based on Fusion Deposition Modelling (FDM) and likewise will borrow from FDM's toolset of printer componentry. 3D Printing is prominent in the maker community; all of the parts required to build an FDM 3D printer can be sourced easily from one of many online maker outlets. Many of these components can be repurposed for this project, however some components, such as the stepper motor, cannot interface with the robot's control system directly. These components will require a microcontroller or additional control modules in the robot's cabinet to function.

Many of the precedent works, such as Ji Shi's Robotic Construction and Bartlett School of Architecture, used Arduino microcontrollers to handle all of the functions of their electronic components. Arduino is also widely used in the maker community to power a wealth of popular 3D printers, such as the printer used for this project. Arduinos must be programmed to perform specific functions using their proprietary code and software.

One method of controlling the extruder is to program the behaviour from scratch, another is to use open-source firmware options available for Arduino to control 3D printing behaviour. As this project requires large amounts of experimentation, a popular open-source printing firmware, Marlin, will be used. Marlin can be customised to most common FDM printer parts and is designed to read G-code through serial communication with a printing host program on an attached computer. The robot is not capable of this task so instead this process will have to run in parallel with the robot's actions. As a result, the design software will need to output G-code commands that Marlin will interpret and read the responses from Marlin indicating when those commands have been completed. For this I will use Firefly Experiments: a comprehensive set of software tools that bridge the gap between Grasshopper and Arduino including serial read and write functions for the Arduino Mega. This will enable Grasshopper to serve as the print host by co-ordinating G-code extrusion commands in response to feedback from Marlin via serial communication in real time.

The freeform system must control the extrusion parameters and a basic set of extrusion commands such as extrude, pause and retract to adapt to specific material characteristics These extrusion commands must be co-ordinated with the robot's movements to ensure that they are performed precisely at their intended times and locations. To orchestrate the alignment of these operations they must either be coded to run using time-based commands and initiated simultaneously, or one of the systems must trigger an action in the other.

HAL Robotics features real-time control over the robot by acting as a print host and sending the robot's RAPID commands from within Grasshopper. HAL also has an array of trigger functions that can be used in this way to both send and receive commands at defined points along the robot's path or when a parameter meets a certain condition. These triggers will be used to send commands to the extruder through Firefly Experiments in real-time, and by using G-code commands as the method to control the extruder this allows full use of all the existing G-Code functions of Marlin.

Figure 36: Arduino MEGA 2560 Taurino 24V (RobotDigg, 2018)

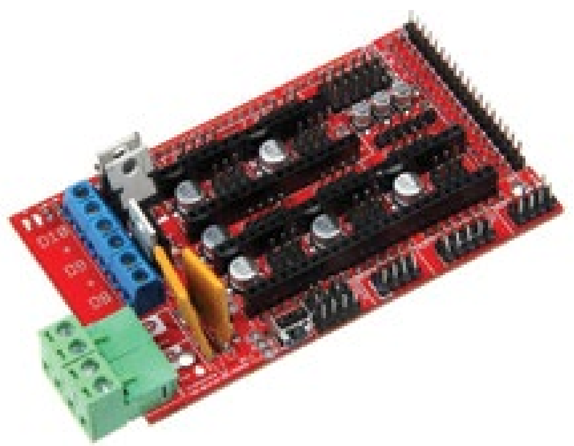


Figure 37: RAMPS 1.4 (RobotDigg, 2018)

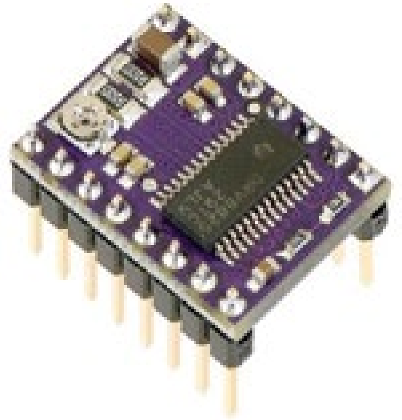


Figure 38: DRV2285 Stepper Motor Driver (RobotDigg, 2018)

Figure 39: 5:1 Geared NEMA 17 Stepper Motor (RobotDigg, 2018)

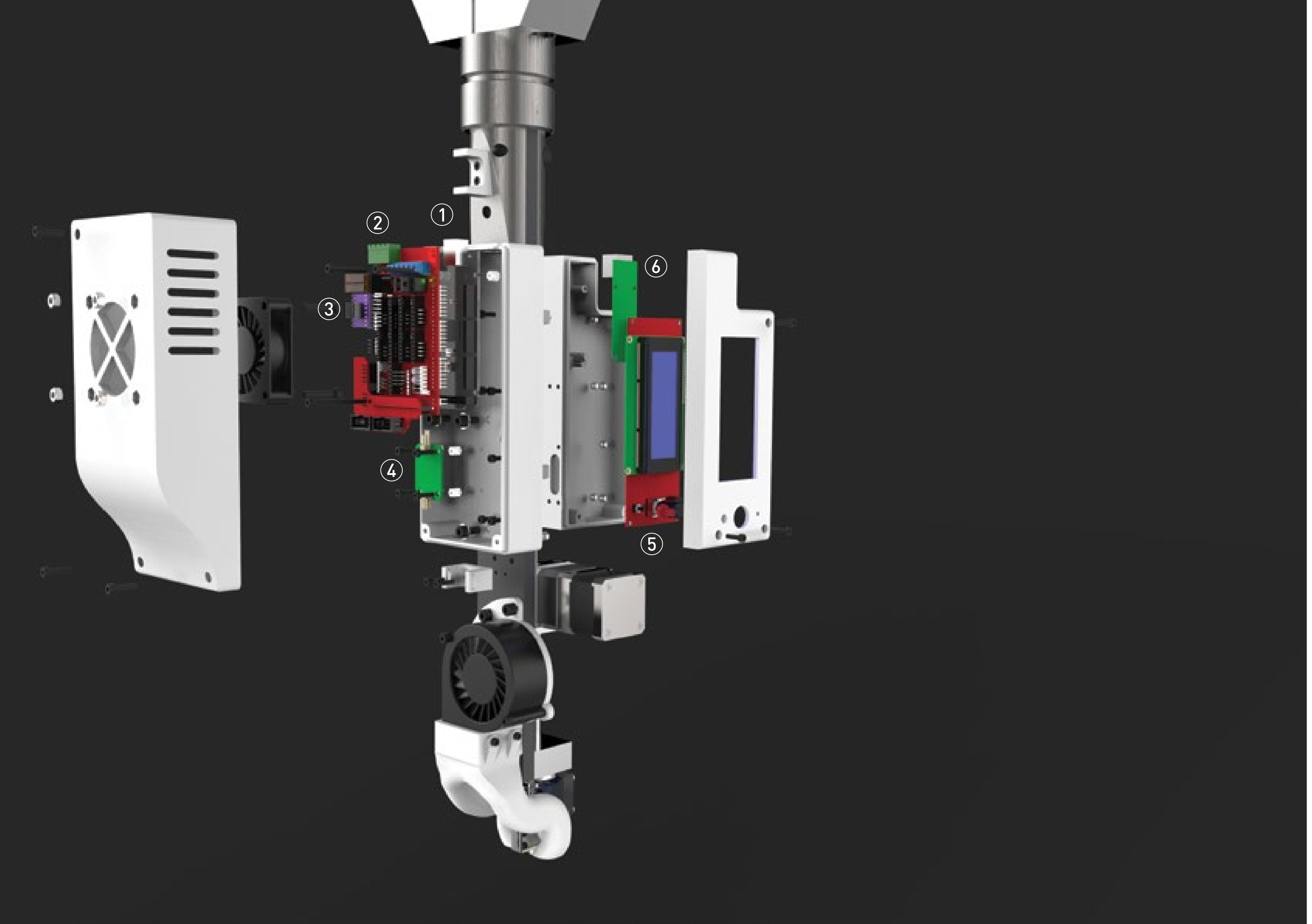
Figure 40: E3D v6 Hotend (E3D, 2018)

BUILDING A FREEFORM SYSTEM - SELECTING COMPONENTS

After reviewing popular variations of Arduino CNC chipsets, the most suitable and adaptable was the Arduino 2560 Mega chipset paired with the Reprap Arduino Mega Pololu Shield (RAMPS). As the robot's digital I/O module operates at 24VDC the Arduino & RAMPS should be able to handle these voltages for any digital communication between the robot and extruder. The increased voltage allows for higher-performance components that might require a larger throughput - such as the heater cartridges or cooling fans. The Arduino Mega 2560 can be sourced in a 24V version, and the RAMPS can be modified for 24V operation.

The hotend selected for thermoplastic extrusion is the popular open source E3D v6 which is used in a variety of FDM 3D printers available in the market and is compatible with the Arduino and RAMPS. This will result in a quicker build time with proven equipment so that material experiments can be performed and interpreted before further customising the extrusion hardware. E3D offers hotends for both the FDM standard printing material sizes (1.75mm and 3mm) and both of these will be used to give this project access to a broader range of Scion's filament materials as well as commercially available filaments. The nozzles in these hotends will be replaced with custom long nozzles with larger bore sizes that will increase the strength and size of the extrusions and extend the point of extrusion away from the heater block of the hotend so that it is less likely to collide with previously extruded strands.

The extruder used to feed the hotend will be custom made and use a similar mechanism to many open-source and commercial extruders that uses a spring and an idler arm to clamp the filament against a pinch gear. The extruder will be high torque and use a geared NEMA 17 stepper motor with a specially fitting pinch gear from Maker's Tool Works. The motor can be powered by the Arduino and RAMPS and has a known ratio between extruder rotation and extruded filament length which is a constant that can be factored in at the design stage.



TOOL DESIGN - ELECTRONICS

1 : ARDUINO MEGA 2560 TAURINO 24 V

This serves as the backbone of the extruder and controls all of the electronic componentry. It is programmed with Marlin 3D printing firmware and receives G-Code commands that control the extruders behaviour via serial communication from a control computer.

2 : REPRAP ARDUINO MEGA POLOLU SHIELD (RAMPS) 1.4

Open-source 3D printing shield for the Arduino Mega. The RAMPS draws power from a separate 24V power supply and distributes it through high-level MOSFET switches to the fan, heater cartridges and stepper motor driver. The fuses and MOSFETS have been upgraded for 24V operation.

3 : DRV8825 STEPPER MOTOR DRIVER

Control board for the stepper motor. Has multiple microstepping options used to ret the resolution of the stepper motor movements and plugs in to a header on the RAMPS 1.4

4 : PT100 AMPLIFIER

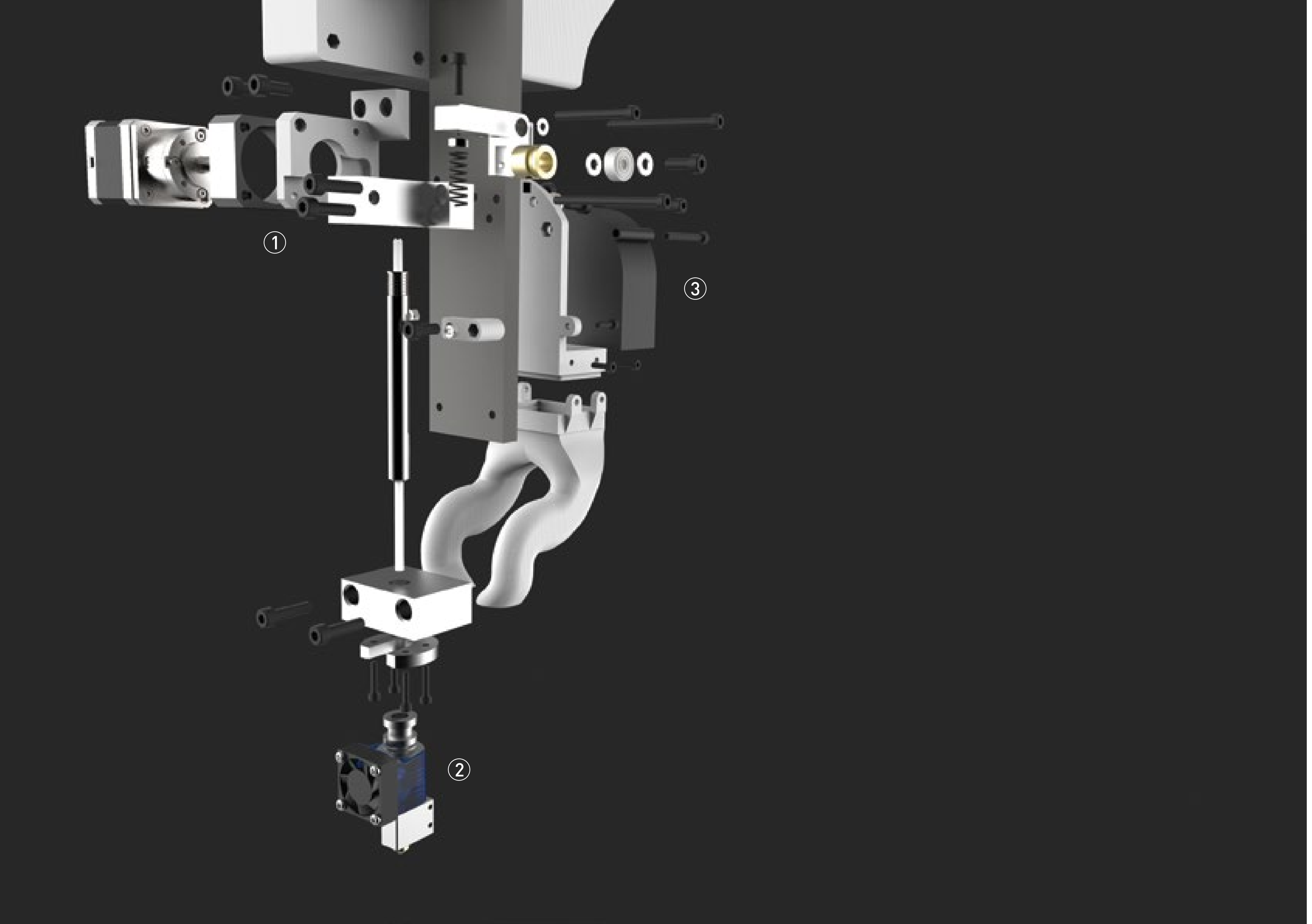
Used to amplify the signal from the thermocouple in the E3D hotend to a 5V signal that the Arduino can read. Connects through the PLC socket into the Arduino's logic level circuitry

5 : LCD CONTROLLER

Provides feedback of extruder parameters, such as temperature, feedrate, and fan speed. Can be used to preheat the hotend and control the extruder.

6 : USB OVER ETHERNET EXTENDER

Converts the USB to run over an amplified ethernet cable, increasing the maximum cable length. Connects to the control computer for sending and receiving G-code commands.



TOOL DESIGN - EXTRUDER AND HOTEND

1 : EXTRUDER ASSEMBLY

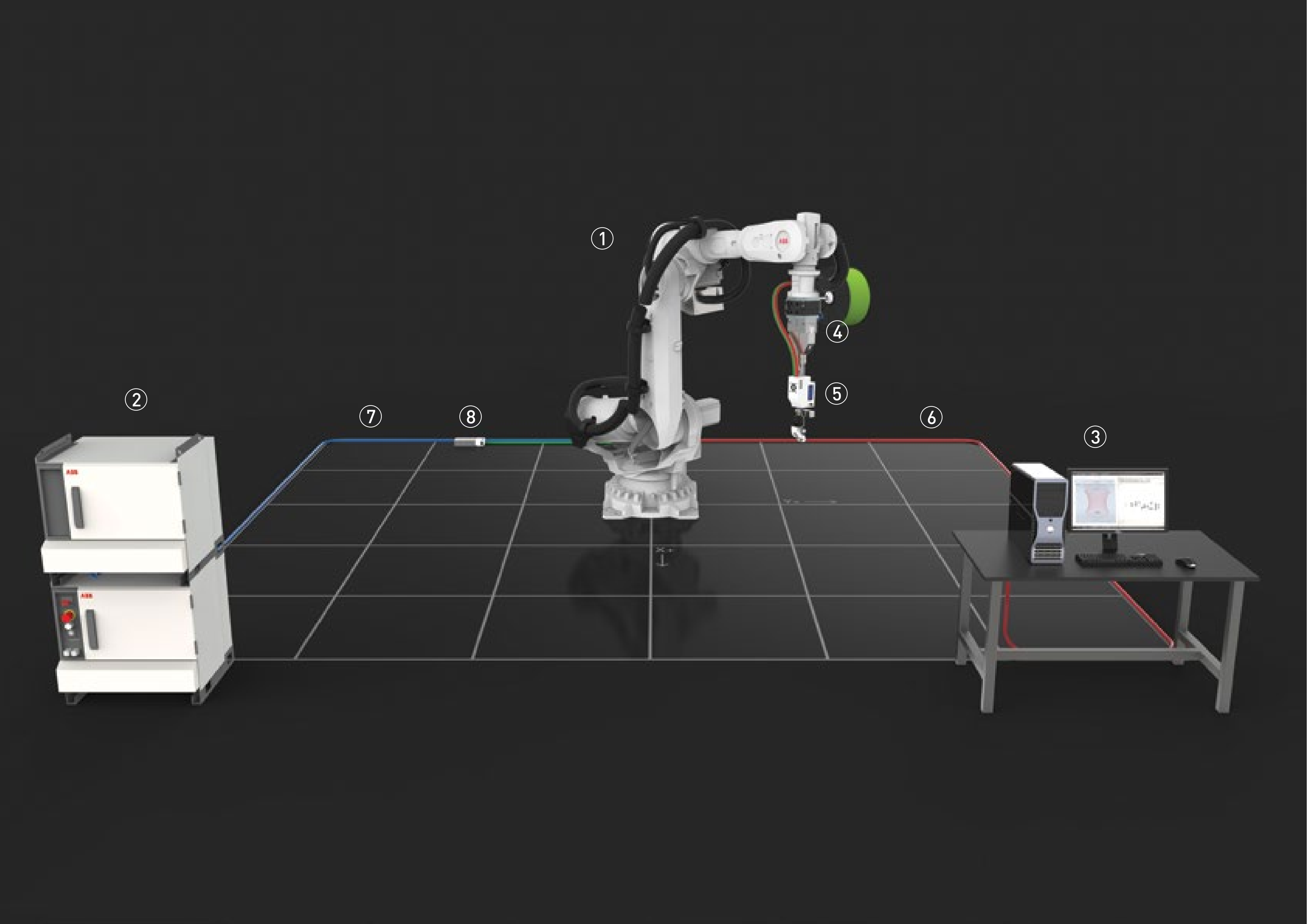
The extruder consists of two main sections; a high-torque geared stepper motor with a brass pinch gear and an idler arm with a bearing compressed by a spring. The bearing on the idler arm presses the filament into the pinch gear forcing it into a PTFE liner tube that feeds the hotend.The extruder can fit a range of filament sizes but the PTFE liner must be changed when swapping filaments

2 : MODIFIED E3D v6 HOTEND

The hotend houses the heater cartridge and thermocouple connected to the Arduino that regulate the temperature of the nozzle. The heater block has been upgraded with high-throughput hardware and a custom long nozzle to prevent collisions with already printed strands. The heater block is also equipped with a high-temperature silicone sock that prevents the heat from radiating from the hotend into printed geometries and creates a barrier that prevents the cooling fan from cooling the extrusion inside the nozzle. The E3D can be interchanged to cater for the standard filament sizes of 1.75mm and 3mm allowing for a wider range of materials that this system can test

3 : BLOWER FAN ASSEMBLY

The blower fan is used to cool the extrusion as soon as it exits the hotend so that material can be placed precisely in free space. The air is channelled through a 3d printed duct to the hotend on opposite sides of the nozzle to help counteract deflection from the airstream pushing on the molten extrudate.



ROBOTIC SYSTEM - OVERVIEW

The spatial printing tool has a number of interfaces within the robotic system which are illustrated in the diagram opposite:

1 : ABB IRB6700 INDUSTRIAL ROBOT ARM

This serves as the base of all movement for the freeform printing tool and is controlled by the ABB IRC5 Control Cabinet

2 : IRC5 CONTROL CABINET

This is where all of the robotics motion and input output signals are controlled from. The control cabinet has a touch pendant where the robot's movements can be jogged and is equipped with additional analog and digital modules for sending and receiving signals with the spatial printing tool. Programs can be uploaded to the control cabinet via USB or uploaded from a host computer via ethernet

3 : CONTROL COMPUTER

Computer used for programming robotic processes and controlling the spatial printing tool. The programs installed on this computer are noted in the Software and Design Environment Overview

4 : PNEUMATIC GRIPPER

The physical attachment for the tool is a turned steel boss that fits into the jaws of the pneumatic gripper that were custom made to grip incremental forming tools from a previous project. When not equipped to the robot these bosses are held by a tool changing station (not shown) that the robot can be programmed to swap between within an automated process

5 : SPATIAL PRINTING TOOL

6 : USB CABLE FOR SPATIAL PRINTING TOOL

This long-distance USB cable is used to send data to the Arduino in real-time and runs parallel to the Robot Control Cabling. Can also upload firmware to the Arduino from the Control Computer. It must be disconnected from the tool before it is removed

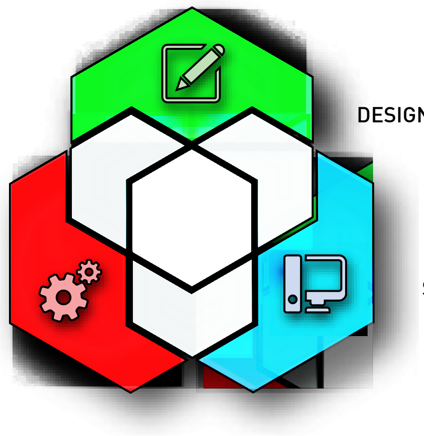
7 : ROBOT CONTROL CABLING

Cabling from the IRC5 Control Cabinet to carry all of the power and signals for the robot's movements and tools. Has a limited number of spare input and output signals

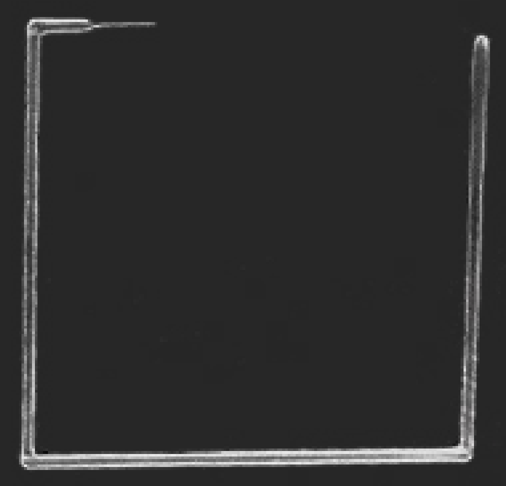
8 : POWER SUPPLY AND CABLE FOR SPATIAL PRINTING TOOL

Separate 24V power supply and cable for the spatial printing tool. It must be disconnected from the tool before it is removed.

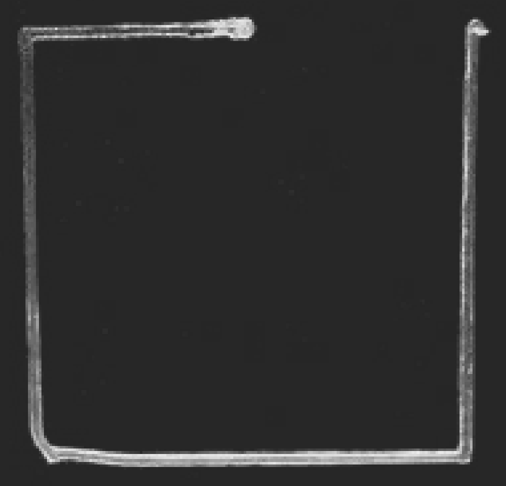
This forms the basis of the robotic freeform system at the core of the Venn Development Diagram:



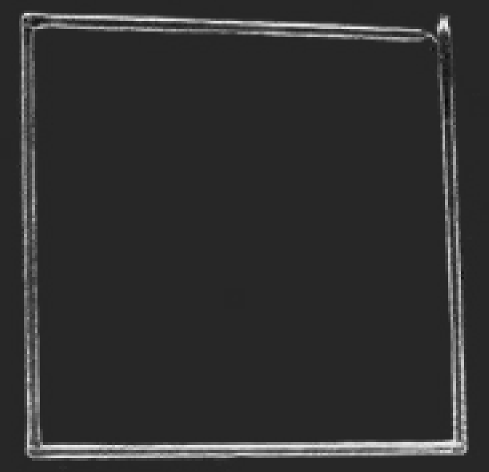
MATERIAL EXPERIMENTS



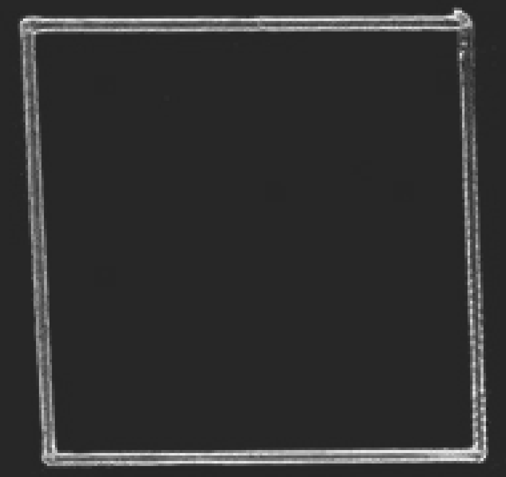
FILAMENT LENGTH 300 MM



FILAMENT LENGTH 350 MM



FILAMENT LENGTH 400 MM



FILAMENT LENGTH 450 MM

EXTRUDER CALIBRATION EXPERIMENTS

AIMS & OBJECTIVES

These initial experiments are for calibrating the extrusion amount for the nozzle and extruder configuration.

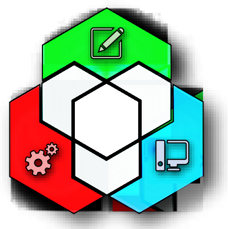
METHOD & VARIABLES

The tests will use a set robot speed and extrusion rate and extrude different amounts of filament until a nominal number is reached where the extrusion completes the square and the extrusion adheres to the print surface. This value will then be used to calibrate the filament/nozzle ration of extrusion and set a nominal line thickness value,

PARAMETERS

MATERIAL : 1.75mm spoolWorks Edge - Clear Crystal
TEMPERATURE : 240C
NOZZLE SIZE : 1.2 mm
EXTRUSION RATE : 500 mm/min
ROBOT SPEED : 10 mm/s
DESIGN MODEL : 100 mm Square

DEVELOPMENT DIAGRAM



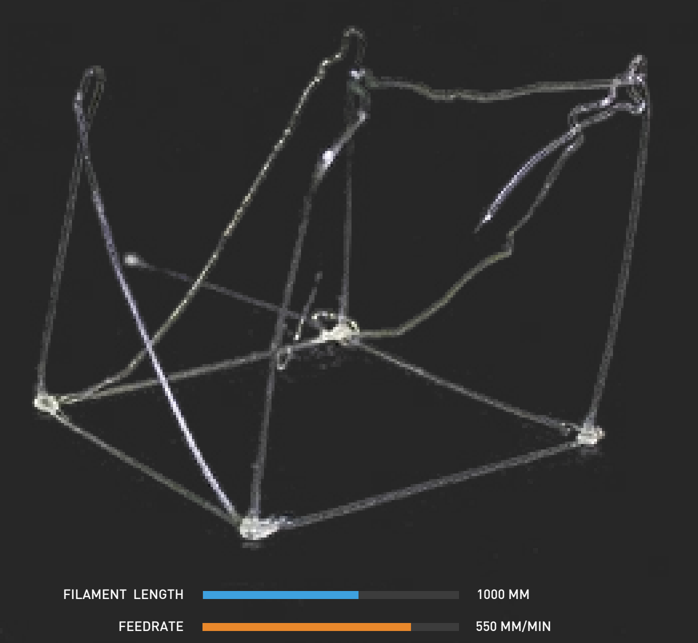
OBSERVATIONS

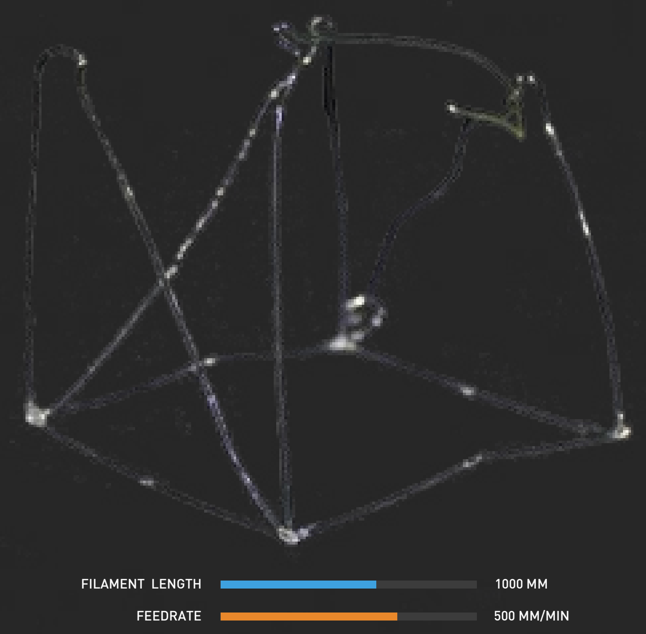
The extrusion rate was enough to make a squashed line so that the extrusion would stick to the print surface at a given distance away from the surface. The initial extrusions fell short of their expected values but were adjusted to perform a full extrusion.

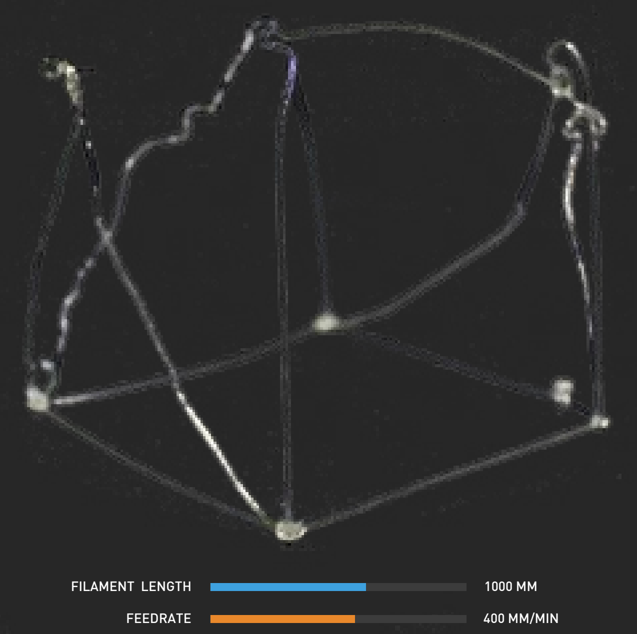
CRITICAL REFLECTION

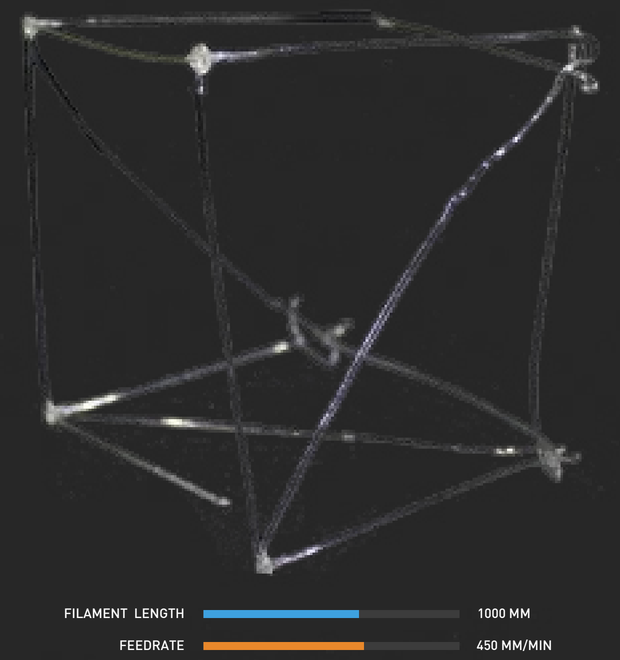
The amount of extrusion required for complete extrusion was found for this 50mm square and will be used to define a more precise relationship between the line length of the model and the amount of plastic to extrude. This relationship must be found if the model is to be printed with different parameters for each strand as the command to extrude in G-Code requires the length of filament and accompanying feedrate as an input.

Every time the filament size or nozzle size is changed the relationship between filament input to extrusion output is changed and these tests must be repeated.









SPATIAL PRINTING EXPERIMENTS I

AIMS & OBJECTIVES

This set of tests will attempt to print a simple free-standing geometry without the use of support materials to determine if this configuration is capable of freeform printing.

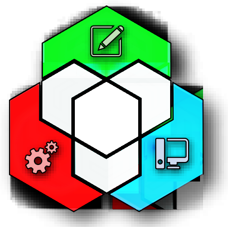
METHOD & VARIABLES

Using a constant robot speed, these experiments will vary the extrusion lengths and extrusion speed to achieve an extrusion that is self-supporting and solidifies where intended. Printing this simple cube involves printing vertical strands, overhangs, and onto a flat substrate so that the various dependencies can be investigated.

PARAMETERS

MATERIAL : 1.75mm spoolWorks Edge - Clear Crystal
TEMPERATURE : 240C
NOZZLE SIZE : 1.2 mm
EXTRUSION RATE : 500 mm/min
ROBOT SPEED : 7 mm/s
DESIGN MODEL : 150 mm Cube
COOLING : 23.1 m^3/h

DEVELOPMENT DIAGRAM

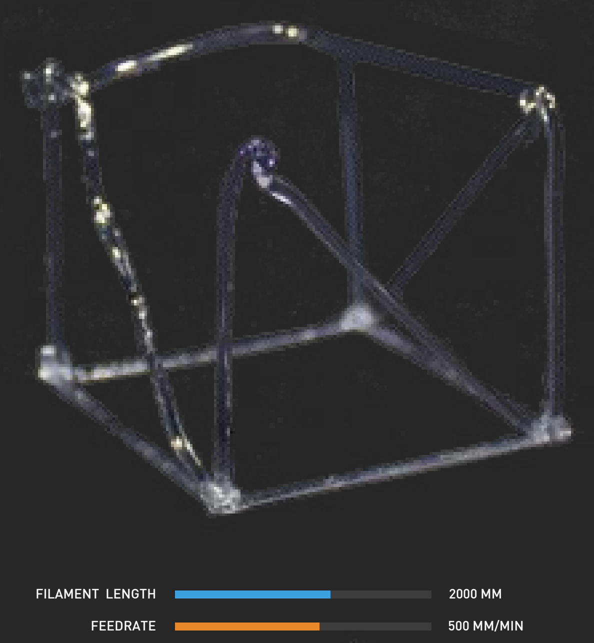


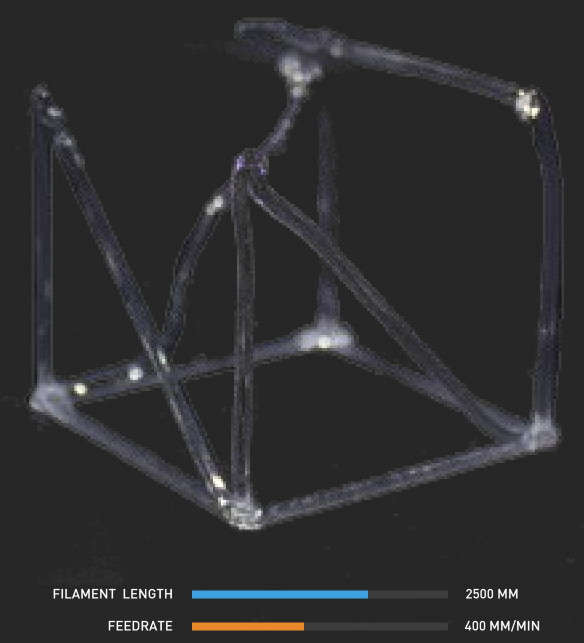
OBSERVATIONS

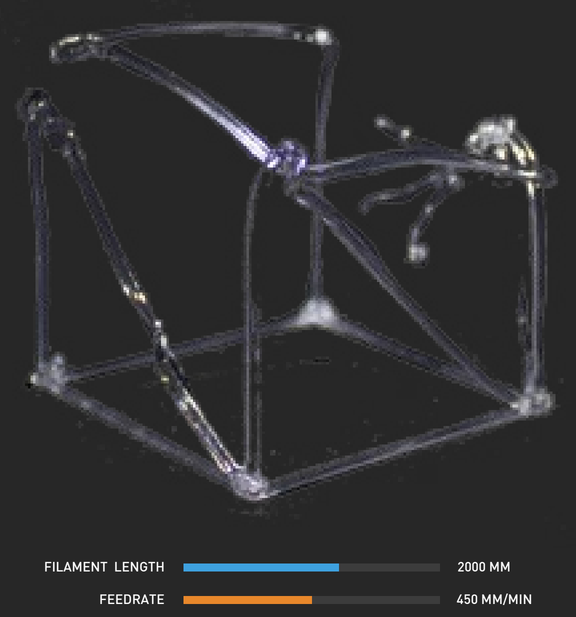
When extruding into free space, the thickness of the extrudate exiting the nozzle tends to remain constant and very close to the size of the nozzle. If the plastic is extruding too fast for the robot's speed, the vertical strands bend outward away from the nozzle, and the overhangs extrude back and forth away from the nozzle creating a wavy pattern. If the extrusion is too slow the strands become thinner and detach easily from the print surface.

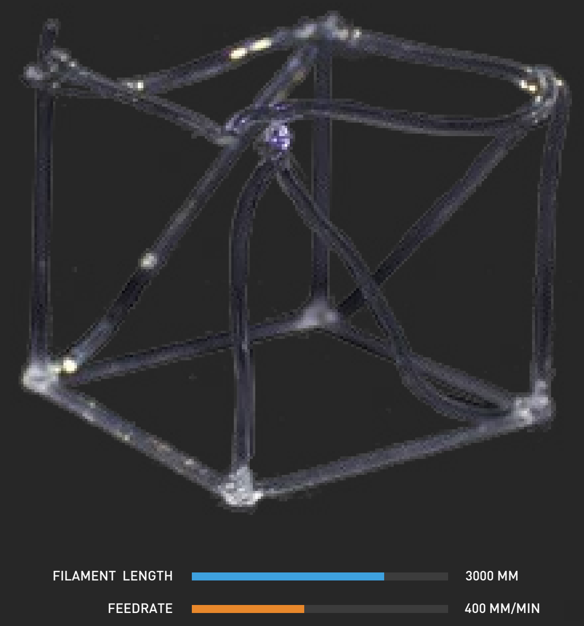
CRITICAL REFLECTION

Printing in free space would appear to have a nominal speed depending on the material, robot speed, and the size of the overhang which all affect the rate at which plastic is extruded. Also, the current extrusion thickness does not seem to have enough strength to hold up a cube of this size so the next experiments will feature smaller geometries. Although the physical nozzle / filament ratio is already known, the exact amount of plastic needed to print a full extrusion can vary due to the slight bulging the extrusion has exiting the nozzle as well as these other factors which will need to be assessed. The variables of interest become the rate of extrusion in relation to the speed of the robot; a finely tuned balance of material deposition and robot speed should result in even extrusions with minimal deformation.









SPATIAL PRINTING EXPERIMENTS II

AIMS & OBJECTIVES

This set of tests will attempt to print a simple free-standing geometry without the use of support materials to ascertain functional variables for freeform printing.

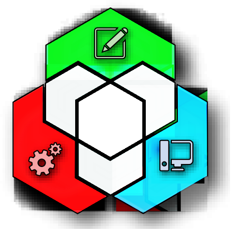
METHOD & VARIABLES

Using a constant robot speed, these experiments will vary the extrusion lengths and extrusion speed to achieve an extrusion that is self-supporting and solidifies where intended. This is similar to the previous experiment except with a smaller cube and slower robot speed.

PARAMETERS

MATERIAL : 1.75mm spoolWorks Edge - Clear Crystal
TEMPERATURE : 240C
NOZZLE SIZE : 1.2 mm
ROBOT SPEED : 2 mm/s
DESIGN MODEL : 50 mm Cube
COOLING : 23.1 m^3/h

DEVELOPMENT DIAGRAM

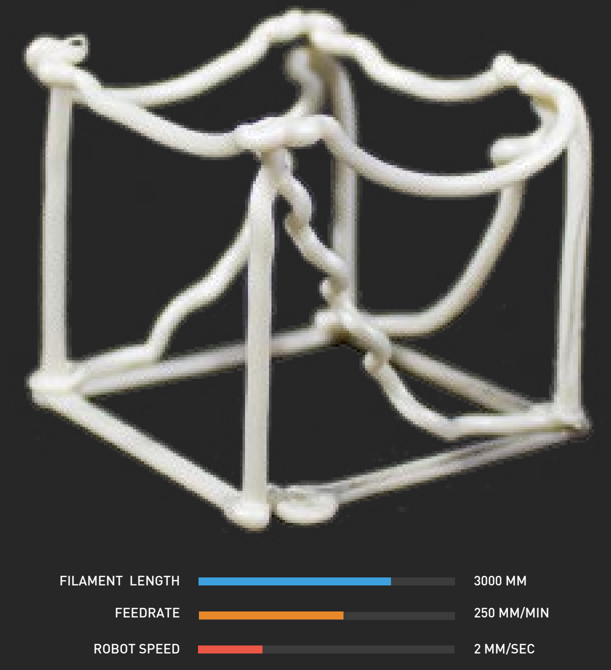


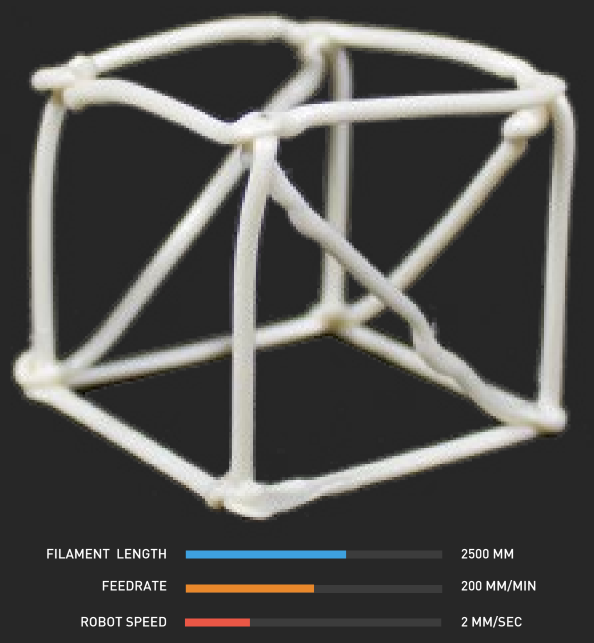
OBSERVATIONS

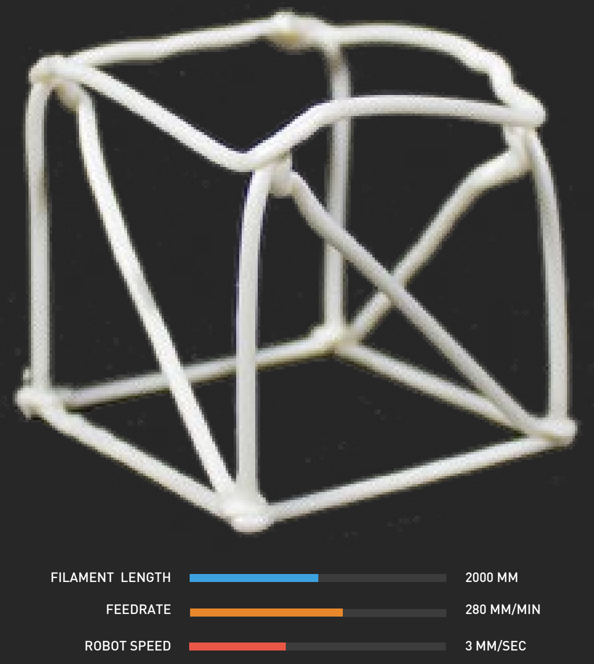
When extruding into free space, the thickness of the extrudate exiting the nozzle tends to remain constant and very close to the size of the nozzle. If the plastic is extruding too fast for the robot's speed, the vertical strands bend outward away from the nozzle, and the overhangs extrude back and forth away from the nozzle creating a wavy pattern. If the extrusion is too slow the strands become thinner and detach easily from the print surface.

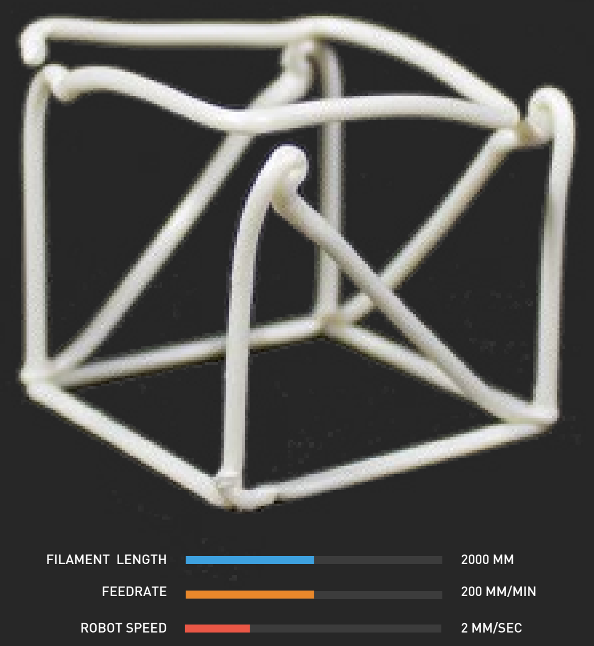
CRITICAL REFLECTION

Printing in free space would appear to have a nominal speed depending on the material, robot speed, and the size of the overhang which all affect the rate at which plastic is extruded. Also, the current extrusion thickness does not seem to have enough strength hold up a cube of this size so the next experiments will feature smaller geometries. Although the physical nozzle / filament ratio is already known, the exact amount of plastic needed to print a full extrusion can vary due to the slight bulging the extrusion has exiting the nozzle as well as these other factors which will need to be assessed. The variables of interest become the rate of extrusion in relation to the speed of the robot; a finely tuned balance of material deposition and robot speed should result in even extrusions with minimal deformation.









SPATIAL PRINTING EXPERIMENTS III

AIMS & OBJECTIVES

These tests will attempt to improve on previous experiments by using larger filament with a wider nozzle size to print thicker and stronger extrusions that will enable the freeform printing process.

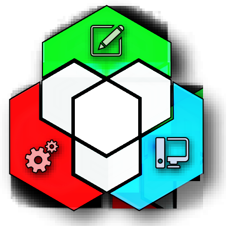
METHOD & VARIABLES

The hotend of the extruder has been swapped out with a version e3D Volcano that uses standard 3mm filaments and a new 2.8mm nozzle was made to print thicker extrusions. These experiments will attempt to find nominal extrusion values for the new filament size, nozzle and material. They use the same geometry as previous experiments and have estimated extrusion rates, filament lengths and robot speeds based on the relationships between these variables as found in previous experiments. The material chosen for these experiments is a biopolymer blend which will hopefully have similar printing properties as the Scion biopolymers that will be tested in future experiments

PARAMETERS

MATERIAL : 2.85mm BigRep PRO HT - Natural
TEMPERATURE : 200C
NOZZLE SIZE : 2.8 mm
DESIGN MODEL : 50 mm Cube
COOLING : 23.1 m^3/h

DEVELOPMENT DIAGRAM

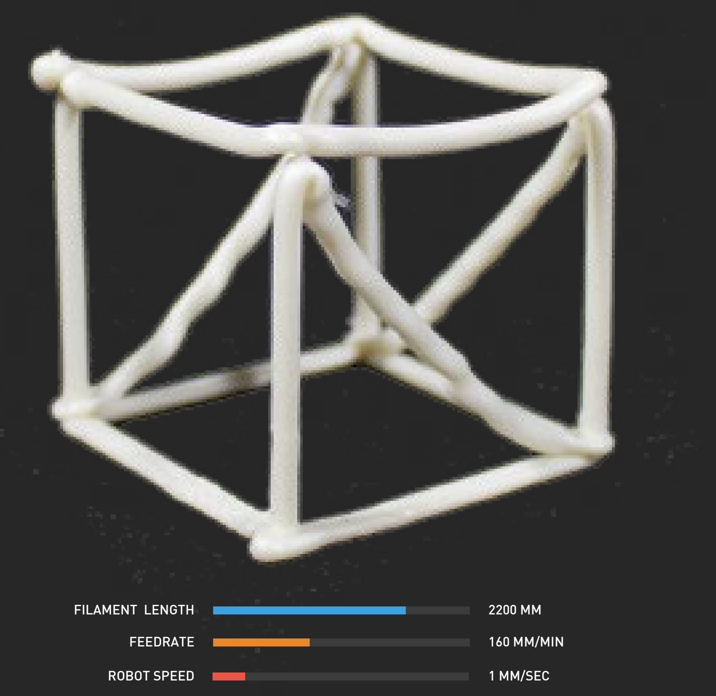


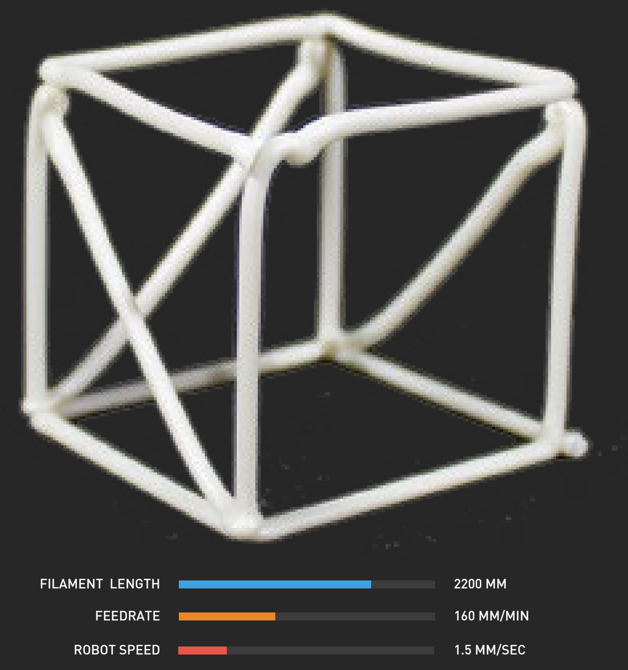
OBSERVATIONS

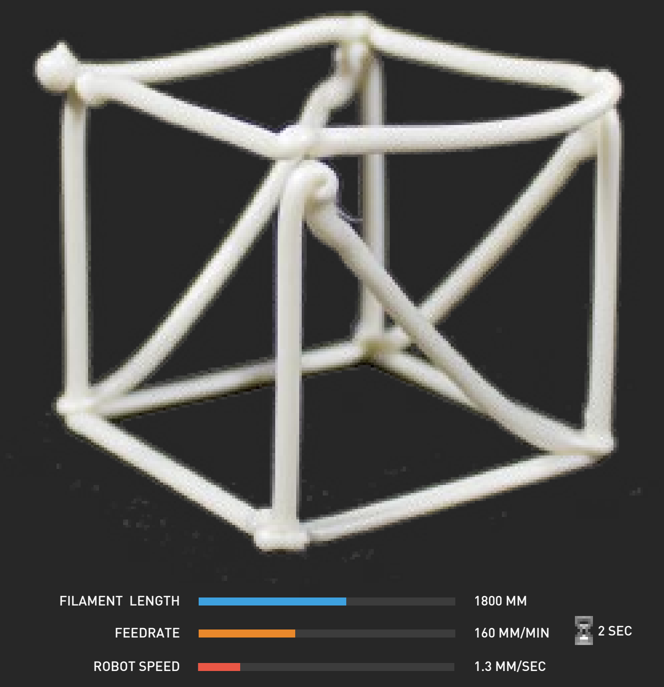
These structures have improved self-supporting properties and better resemble the digital model. The extrusion rate had to first be adjusted in response to the slower robot speed, and again to suit the vertical and overhanging strands. The material is knurled at the top of each vertical strand due to the material not cooling enough before the robot changes direction, and the liquid material sticks to the hot nozzle as it descends because of the shape of the nozzle and its normal alignment to the print surface.

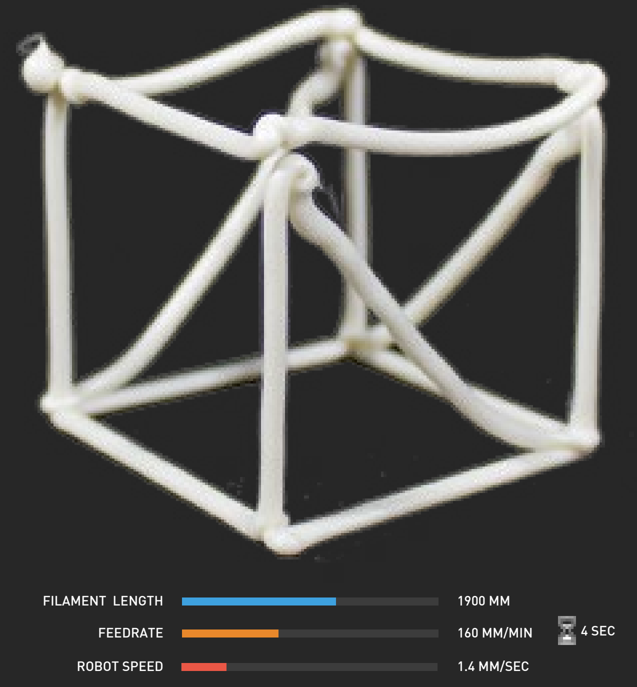
CRITICAL REFLECTION

The smaller cube size proved to be able to support itself better than the larger cube sizes. Values for extrusion rate and length were found that allowed free-standing structures to be printed, but the resulting models are very weak and flexible which in turn makes it difficult for subsequent extrusions to adhere where the strands meet. Stronger strands would help with making the geometries more printable which could be achieved by improving the cooling, decreasing the size of the geometries, increasing the nozzle size or experimenting with a different material. Ideally the thickness of the extrusion would be much larger to improve the strength, however the extrusion diameter is ultimately limited to the size of the filament used which in this case is 1.75mm









SPATIAL PRINTING EXPERIMENTS IV

AIMS & OBJECTIVES

These experiments will attempt to hone in on the best print speed for the current extruder and material configuration and test the effect that pauses in the robot's movement have on printability.

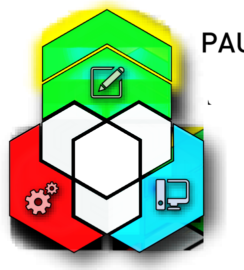
METHOD & VARIABLES

These experiments will continue to focus on the relationship between extrusion rate and robot speed. Once a functional value is achieved I will insert pauses in the robot's movement at the top of each vertical extrusion. This will allow extra time for the material to cool and reduce deformation from ensuing movements. As the extrusion is constant, this should mean additional material is deposited at each node leaving more material for subsequent extrusions at that node to bond to.

PARAMETERS

MATERIAL : 2.85mm BigRep PRO HT - Natural
TEMPERATURE : 200C
NOZZLE SIZE : 2.8 mm
DESIGN MODEL : 50 mm Cube
COOLING : 23.1 m^3/h

DEVELOPMENT DIAGRAM

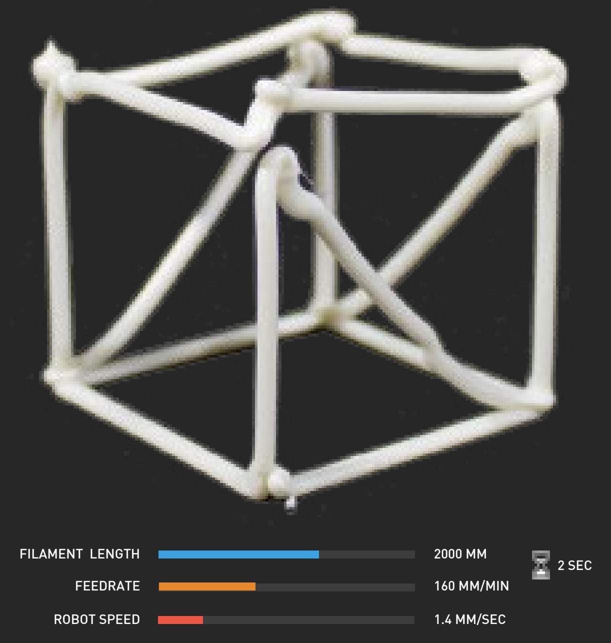


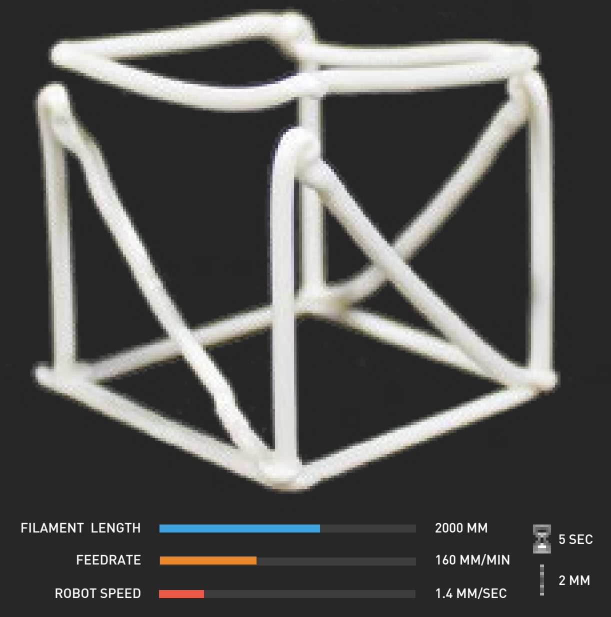
OBSERVATIONS

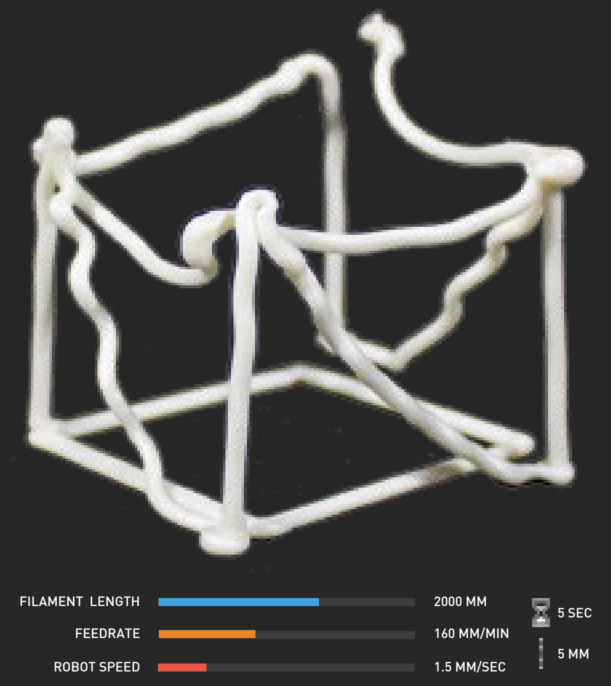
The relationship between extrusion rate and robot speed are close to nominal and the optimal printing speed for the current setup appears to be around 1.3-1.5 mm/s. The pauses at the top of each vertical extrusion allow the material more time to cool, however the material that is still flowing from the nozzle at these points pushes the material that is still cooling away from the intended point of deposition. Once the robot resumes movement, the extra material deposited at the nodes are pulled downward into the next strand causing a slight squiggle at the beginning of the strand's extrusion.

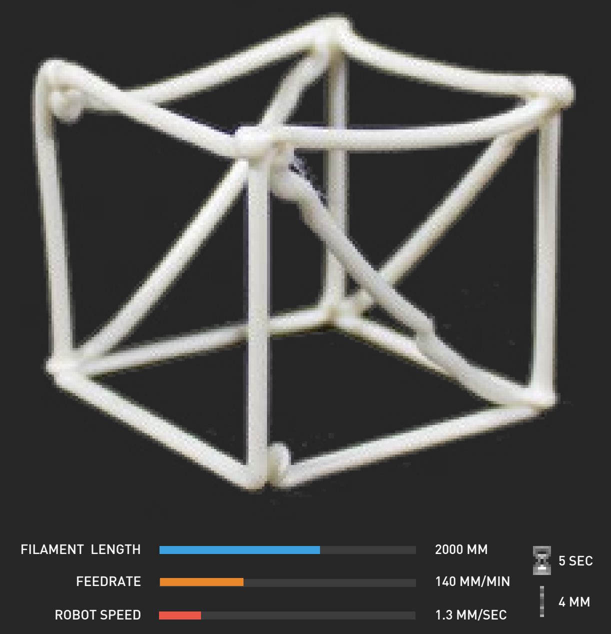
CRITICAL REFLECTION

The increased thickness of extrusions has greatly increased the strength of the strands, and the lower melting temperature of the material (and perhaps the lower heat capacity) allow to material to cool faster post-extrusion. However, the extruded plastic is still viscous as the robot changes direction causing the strands to continue following the nozzle after they've been extruded. Possible improvements could be made increasing the airflow cooling the extrusions, slowing the robot speed down, accounting for this deflection within the design model, lowering the extrusion temperature of the filament or re-orienting extrusion direction of the robot.









SPATIAL PRINTING EXPERIMENTS V

AIMS & OBJECTIVES

The objective of this experiment is to account for the deflection of the vertical extrusions using robotic movements.

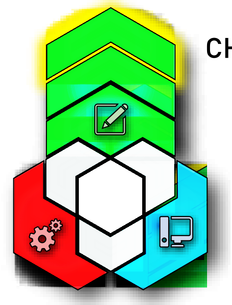
METHOD & VARIABLES

The digital model for these cubes has been modified to account for the gap between the top chord of this cube and the struts that are printed to hold it up. The top chord is adjustable so that it can be offset from the targets for the vertical strands which they are not reaching. These experiments fine tune the extrusion rate and vary the chord offset to investigate the effects on the adherence of the extrusions at the top nodes.

PARAMETERS

MATERIAL : 2.85mm BigRep PRO HT - Natural
TEMPERATURE : 200C
NOZZLE SIZE : 2.8 mm
DESIGN MODEL : 50 mm Cube
COOLING : 23.1 m³/h

DEVELOPMENT DIAGRAM

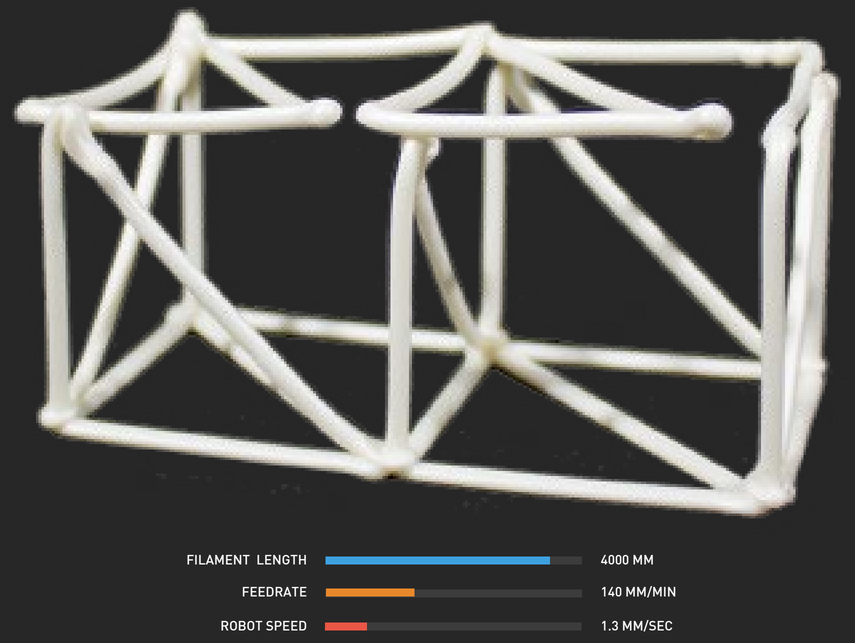


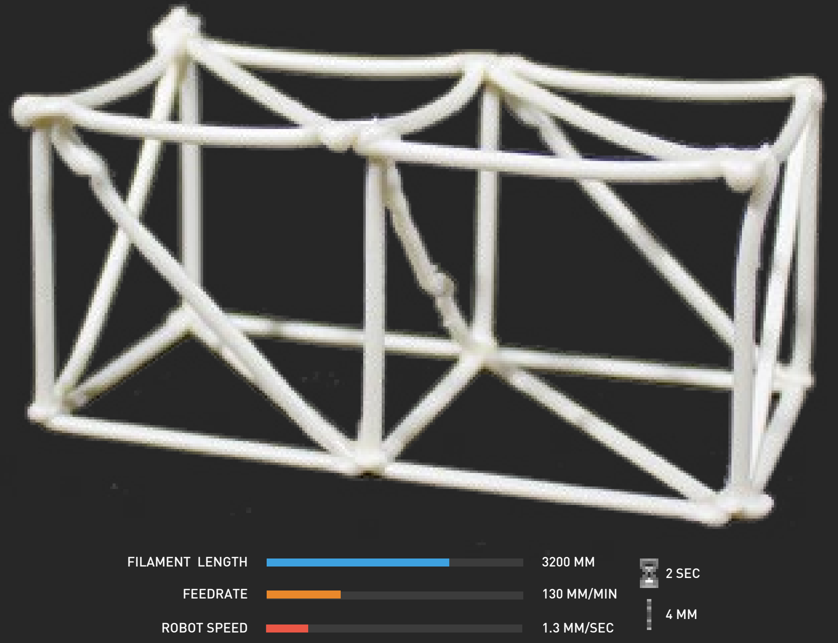
OBSERVATIONS

The chord offset didn't appear to make a difference until the extrusion rate was altered. Increasing the extrusion rate and the chord offset too far caused the strands to form waves and crash into each other. Pulling back the offset and extruding slightly slower created strong bonds in the top nodes of the cube.

CRITICAL REFLECTION

Offsetting the top chord proved to work as a solution for getting the strands to adhere to each other at the top nodes, however this results in a dimensional inaccuracy. This discrepancy can be accounted for in the digital model to prevent generational loss as the structures increase in size or become more complex, but alternative methods of dealing with this issue should also be investigated such as better cooling or robot reorientations. The chord offsets will be used in the following experiments as needed.





SPACE FRAME EXPERIMENTS

AIMS & OBJECTIVES

Investigate the effects that printing larger geometries have on material adherence at the joints.

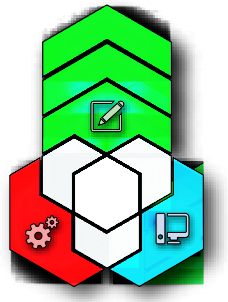
METHOD & VARIABLES

By placing two cubes together that share a wall, this increases the number of strands connecting at the central nodes by two. These experiments test whether this increase in material will aid in materials adhering to each other at the joints and the extent to which the movement delays and top chord offset used in the previous experiments need to be applied.

PARAMETERS

MATERIAL : 2.85mm BigRep PRO HT - Natural
TEMPERATURE : 200C
NOZZLE SIZE : 2.8 mm
DESIGN MODEL : 2 x 50 mm Cube
COOLING : 23.1 m^3/h

DEVELOPMENT DIAGRAM

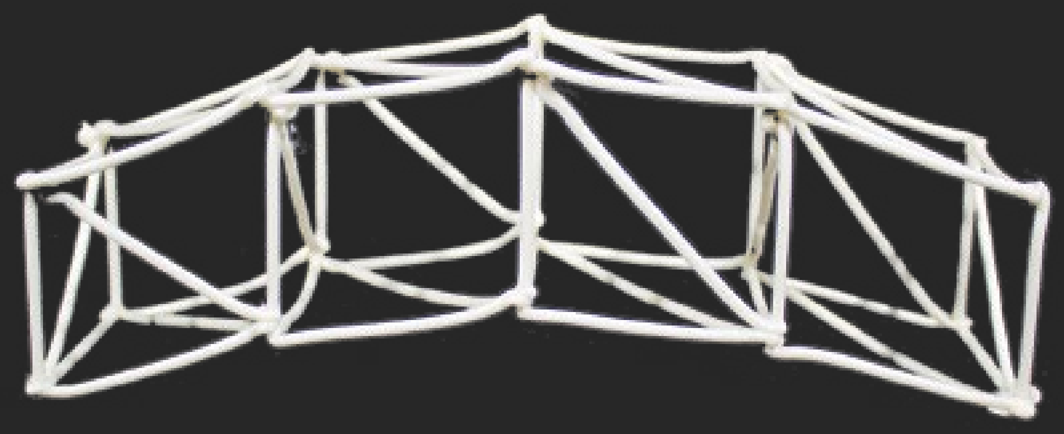


OBSERVATIONS

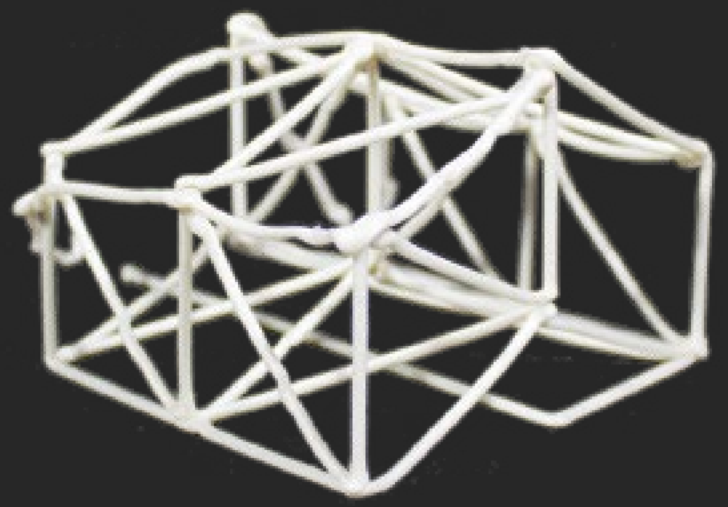
The first print which used the same feed-rate and robot speed as those found to be functional in the previous experiment did not exhibit any bonding in the top nodes of the model. It was also suspected that the feed-rate was still slightly too high for the robot's speed. Decreasing the feed-rate and introducing a chord offset of 4mm and a 3 second delay saw almost all of the top nodes bonding together, yet the joints were still only loosely bonded as the additional plastic from the extra strands and delays caused to curl away from the nodes. Slightly lowering the feed-rate and the pause length resulted in strong bonding from all of the strands at each node.

CRITICAL REFLECTION

The success of these prints appears to be heavily dependent on the length of time that the extrusion remains liquid after leaving the nozzle and what interacts with an extruded strand in that time. The vertical extrusions of these cubes are affected the most by movement or additional extrusion at the end of their paths and regardless of the number of strands that meet at that node deflections of the initial vertical strands away from this point negatively affects the bonding of each other intersecting strand. Ideally the extrusion and robot's movement could be paused simultaneously at these points however the absence of communication between movement and extrusion does not allow for such a co-ordinated process. These experiments successfully account for this by physically accounting for the deflections and by slowing the extrusion rate and robot speed until consistent bonding is observed.



4x1 Cube Bridge



4x1 Cube Bridge

SPACE FRAME EXPERIMENTS II

AIMS & OBJECTIVES

Identify the characteristics of unsupported bottom nodes and strands with large overhangs.

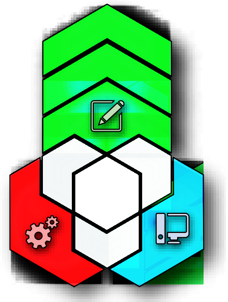
METHOD & VARIABLES

The central nodes of these cubes have been shifted in the z direction so the bottom chords are printed in free space. Only the edges of these models are extruded on to the substrate and the rest of the bottom strands are printed without with overhangs of 45 and 60 degrees. The pauses and offsets for the top nodes will be used as per the results of the last experiment, as well as the extrusion rate and robot speed.

PARAMETERS

MATERIAL : 2.85mm BigRep PRO HT - Natural
TEMPERATURE : 195C
NOZZLE SIZE : 2.8 mm
DESIGN MODEL : 4x1 50 mm Cube Bridge,
2x2 50mm Cube Bridge
EXTRUSION RATE : 130 mm/min
ROBOT SPEED : 1.3 mm/sec
TOP NODE DELAY : 2 sec
CHORD OFFSET : 4 mm
COOLING : 23.1 m^3/h

DEVELOPMENT DIAGRAM



OBSERVATIONS

The 4x1 Cube Bridge printed with no modifications to the printing parameters and exhibited strong bonding at every node. The 2x2 Cube Bridge had a tendency to topple over during printing due to the torques around the points adhered to the substrate so an additional strand was added to the digital model that attaches to the base to relieve the tension, and the resulting print exhibited strong bonding at each node.

CRITICAL REFLECTION

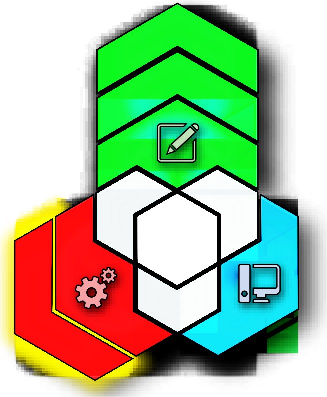
The parameters found as a result of previous experimentation translated well to these structures with minimal support, but care has to be taken to ensure that their designs consider more than the material's behaviour at the nozzle with regards to it's printability. In the case of the 2x2 Cube Bridge the condemning factor in it's printing was the adhesion of the strands on the substrate were not strong enough to deal with the torques around them. This was a minor pitfall for this experiment, however in larger experiments the material's weight force, torques around the substrate, and knocks and bumps from the extruder head must be considered in the design process.

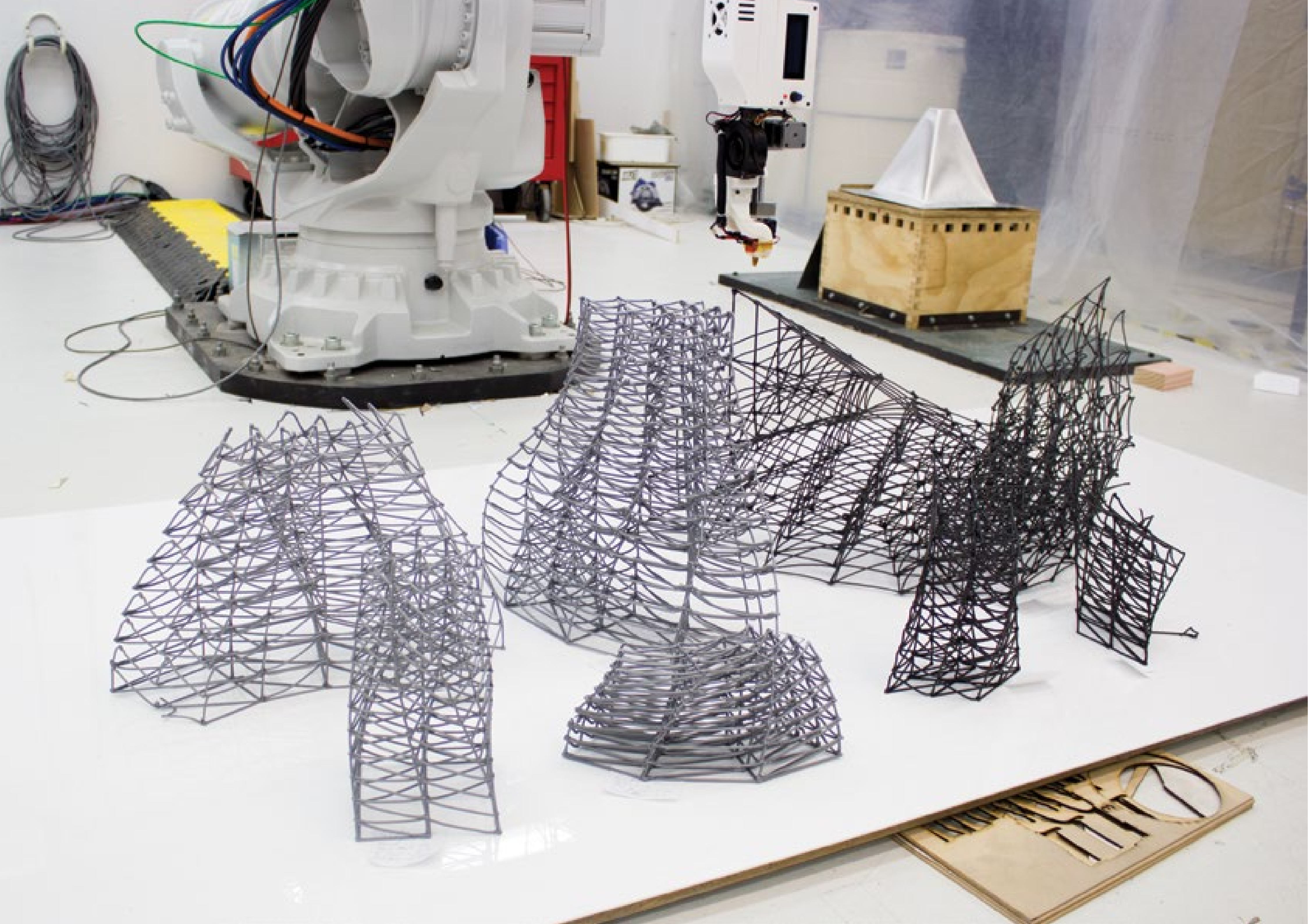
FAN UPGRADE

With the current configuration the system is capable of achieving spatial printing speeds up to 1.3mm/s. This speed must be set unilaterally across movements within each print model as the ability to assign parameters to individual movements has not yet been achieved. At this speed, a 50mm cube model takes a minimum of 15 minutes to complete and a 5x5x5 grid of these cubes takes well over a day, making large-scale models prohibitively time-consuming to print.

To improve the printing speed a new blower fan with over twice the airflow of the original fan has been installed. Performing a condensed set of the previous printing experiments found that the speed for spatial printing could be increased to 1.8mm/s with improved bonding at the nodes. Proportionally this is an increase of 40% reducing the overall printing time of full-scale design objects within an acceptable range. This improvement in the cooling system is illustrated by a red chevron in the hardware section of the development diagram.

COOLING UPGRADE





LARGE SCALE EXPERIMENTS - SPACE FRAMES

With the improvements to the printing speed and bonding at the nodes the system has reached a threshold where printing large-scale spatial structures is now feasible. To test this, the system has been entrusted to Armano Papageorge – an Architecture masters student who is exploring the architectural outputs of this system by printing various space frames with curved geometries. Shown opposite is a selection of these frames that are printed using the parameters found by the results of experimentation thus far.

Each space frame experiment exhibits good bonding at the nodes with strong mechanical properties when printed with the same biopolymer materials used throughout testing. The experiments range in size from 3 x 3 x 3 cube models to 1m x 1m wall sections, taking anywhere between hours and days to complete.

These experiments prove the system to be capable of generating large-scale spatial structures with complex geometries using biopolymers. However, despite the level of complexity of these space frames, this research was ultimately limited to defining each model using only a single toolpath with a set extrusion rate due to a lack of communication between the extruder componentry and control cabinet. These experiments are included for discussion in the following sections.

EXPERIMENTS I - DISCUSSION

ROBOTIC SYSTEM

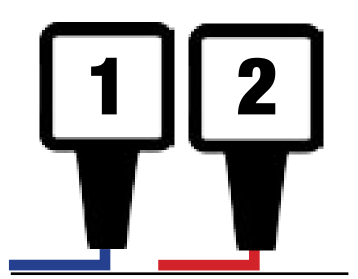
Over the course of experimentation, the extruder was found to be capable of a wide variety of spatial structures using several different materials. However, many of the initial assumptions about connections between programs and components in the robot system were found to be false, and programs such as Firefly Experiments and HAL Robotics did not operate as expected. For example, Firefly's Serial Read component could not receive the responses sent by Marlin from the Arduino to form the feedback loop for aligning the robot's movements. Also, HAL Robotics is not yet able to receive live commands from Grasshopper or parametrically generate lists of attributes in the same way as other Grasshopper components.

As there is no connection between the two systems, the feed-rates have been set at a constant speed and left to run continuously throughout each experiment. Communication between the robot and the extruder has not been possible as the behaviour for setting extrusion rates is controlled by the Marlin firmware and requires a total restructuring of the code to function as intended. Additional cabling is also required to transmit the signal from the robot's control cabinet to the end-effector, the behaviour of which must be programmed in the RAPID code that the robot runs on and interpreted by the Arduino.

Without this level of communication, experimentation with materials and structures is limited to design-based solutions, hardware alterations and modifying the initial printing conditions. Whilst the optimal printing conditions can be found through tests and calibration, the optimal printing settings can't be implemented beyond a single feed-rate : movement speed relationship. In turn, the design models for printing must be low-resolution and cannot make use of any adaptive behaviours that the Arduino could facilitate using a basic level of communication with the robotic control system.

The spatial printing system is limited in its capacity to generate objects with a large degree of design complexity and it is not able to successfully print using Scion's biopolymers. So the system will be redesigned completely in an attempt to improve on the limitations found during initial testing. The discussion for the development of the second extruder system is outlined on the following page.

DISCUSSION - SPATIAL PRINTING SYSTEM



MULTI-PROCESS MANUFACTURE

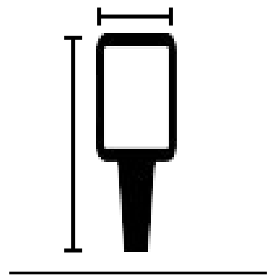
- Call for using multiple processes together in constructing artefacts by using the robot’s tool changing system, e.g. combining automated extrusion \ milling \ pick and place \ nailing operations

- Need for an automated method of cutting the fibre core in coextrusion filament to allow for both separate printing movements within the print and processes with other tools.

SECOND EXTRUDER CRITERIA

- Development of a universal tool-changing system into extruder design

- Programming an industrial microcontroller to control different end-effectors through an electrical tool changing module on the robot



IMPROVED FORM FACTOR

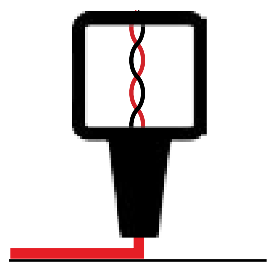
- Need to improve the resolution of prints using a “sharper” extruder that will avoid collision with already-printed geometries

- Need for an extruder with a smaller tool centre point (TCP) to improve positional accuracy of the extruder nozzle and enable faster planar alignments of the extruder

SECOND EXTRUDER CRITERIA

- Development of new extruder hardware with a focus on small TCP distance

- Development of compact hotend and cooling hardware with a focus on sharp profile



SUPPORT FOR CO-EXTRUSION FILAMENT

- Hardware must be flexible and adaptive to the changing parameters of material experiments

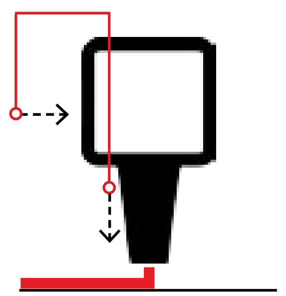
- Fibre cores of co-extrusion filaments need to be cut at the end of extrusion movements to allow the nozzle to travel

- Nozzles need to have an equal ratio of filament input to extrusion output for coextrusion filament experimentation

SECOND EXTRUDER CRITERIA

- Make nozzles for co-extruded filaments that help prevent material clogging

- Develop a system for changing the core of the extruder to cater for a range of filament sizes



AUTOMATED EXTRUDER BEHAVIOUR

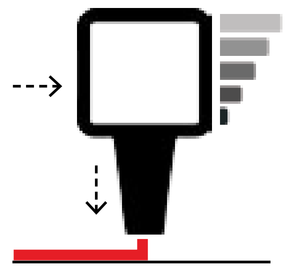
- Extrusions must be precisely aligned with robotic movements so that different extrusion parameters can be assigned to each movement

- Need for a feedback loop for temperature control, extruder movement speed, cooling rate and robot positioning

SECOND EXTRUDER CRITERIA

- Install cabling and electronic tool changing modules that facilitate digital\analog communication between control cabinet and robot end-effector

- Automate the spatial printing behaviour in response to digital and analog signals from the control cabinet



VARIABLE PRINT PARAMETERS

- Need for variable robot speeds and extrusion rates to account for different movement types (vertical, bridging, substrate, travel, etc.)

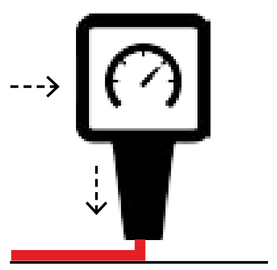
- Need for automated extruder and robot behaviour including programmable pause, travel, and substrate printing processes

SECOND EXTRUDER CRITERIA

- Automation of print speed adjustment based on experimental data of deflection due to gravity

- Automation of speed declarations, pause insertion, travel movements and toolpathing calculated from design input

- Automation of RAPID code generation for spatial printing processes



FASTER PRINTING

- The speed of spatial printing must be improved to shorten the overall print time and enable larger prints

- Extruded materials need to be cooled quicker and more precisely

SECOND EXTRUDER CRITERIA

- Develop hardware that cools the extruded material at the tip of the print nozzle using the robotically controller compressed air lines

- Trials of materials with lower melting temperatures to expedite the spatial printing process

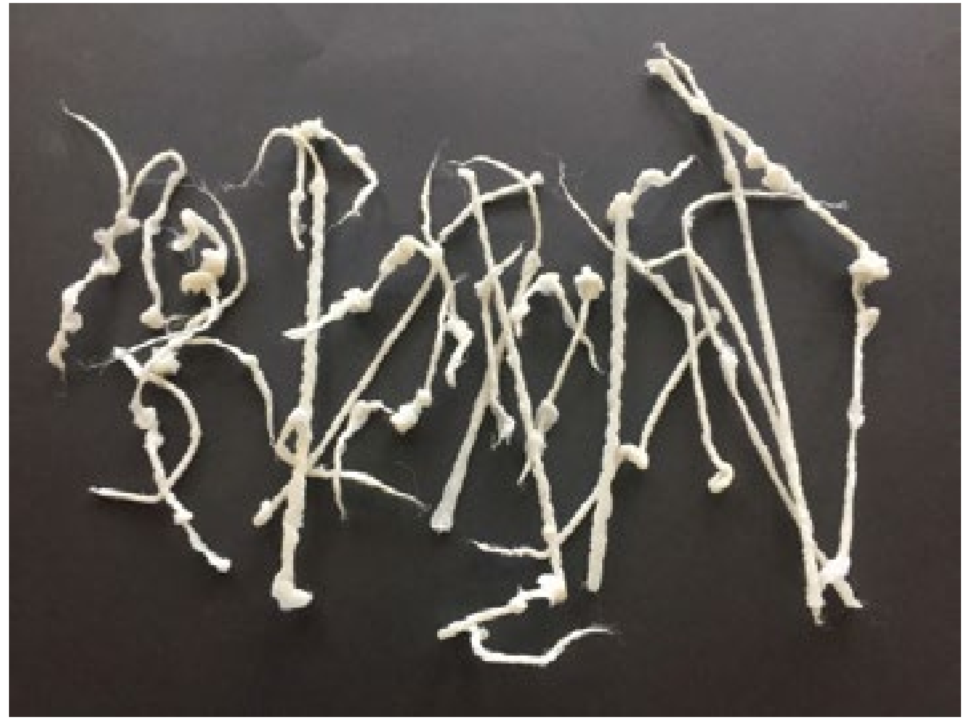
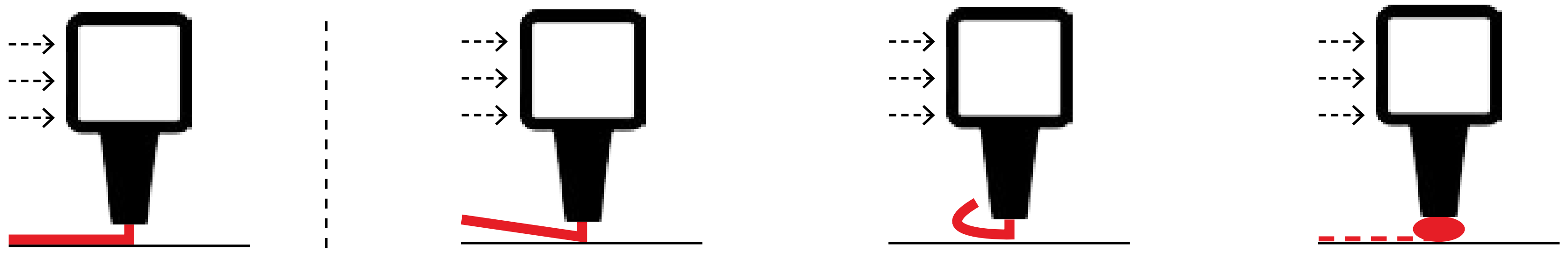


Figure 41: Author, Co-extrusion Filament Experiments

DISCUSSION - MATERIALS

The experiments tested a variety of materials for their capacity to print in free space using the freeform printing system including PLA, ABS, PETG and biopolymer-PLA blends. Bigrep's ProHT BioPolymer material was found to have the most robust spatial printing qualities and the most similar material characteristics to Scion's materials, and was thus used throughout the majority of printing experiments.

The custom biopolymer materials were tested using the same simple cube models and similar constraints as the ProHT experiments. The biopolymers are supplied as co-extrusion filaments. These differ from the ProHT reference material by having a lower melting temperature by up to 70 degrees, and have natural long fibres at the core of the filament. These long fibres give the filament additional tensile strength which is a desirable craft property for the output design models. However, the addition of the fibre core requires the extrusion toolpath to be continuous. This often causes bubbling of the liquid thermoplastic around the fibre during extrusion resulting in an irregular filament shape and extrusion profile. After extensive testing, the custom co-extrusion materials were not found to be effective for printing spatial structures using this extrusion equipment. Illustrated below is a review of the complications with this material:



Desired Output
Consistent Extrusion

Actual Output
Substrate Delamination

- Extrusions delaminate easily from the substrate and require additional adhesion agents to adhere for the duration of the print

- "Squashing" the extrusions onto the substrate for better adhesion results in clogging due to the long fibres

- Tension from the long fibres can cause the extruder to pull on the print causing it to delaminate from the substrate

Actual Output
Curling Extrusions

- Limited adhesion to the substrate causes the extrusion to pull away from the point of deposition

- Higher extrusion temperatures cause the material to bubble leaving an irregular extrusion profile

- Extrusion speed must be precisely calibrated to match the robot speed; as the fiber core is inextensible the filament input must equal the extrusion output else either the thermoplastic material clogs the nozzle or extruder pulls on the printed structure causing it to delaminate from the substrate

Actual Output
Nozzle Clogging

- Low melting point of material causes it to solidify quickly. Whilst this is ideal for spatial printing it also requires the print speed to be faster or fan sped to be lower otherwise the material clogs in the nozzle

- Irregular filament shape and lumpiness offers little control over extrusion and the cross-sectional area of the filament often exceeds the internal diameter of the PTFE lining of the extruder. This has the capacity to clog the nozzle and sometimes will not fit inside the extruder causing it to jam


EXPERIMENTS II

DESIGNING A SECOND SPATIAL PRINTING SYSTEM - CORE DECISIONS

The most significant improvement that can be made over the previous spatial printing system is to create the connections between each of the components in the system such that the extruder's behaviour can be controlled and aligned with the robot's movements. Typically, end-effectors used by the robot arm are controlled by signals from the ABB control cabinet by using digital signals as a Boolean switch to start or stop a process, and analog signals to set speeds and rates. As such, this extruder will use the same communication methods as the robot's existing end effectors (such as the pneumatic grippers) and will be designed with this requirement as a fundamental hardware constraint.

Modifying the Arduino's firmware to receive commands from the control cabinet in this way requires a complete restructuring of the Marlin code, and the RAMPS 1.4 would have to be modified to accept the voltages of the cabinet's signals. Instead, this spatial printing tool will use an industrial microcontroller that operates at the same voltages as the ABB control cabinet and the tool will be programmed from the ground up using the incoming connections as a starting point. The behaviour of the tool can then be customised to respond to the signals from the control cabinet, including setting the tool to extrude at different rates in time with the robot's movements.

The spatial printing tool will attach to the robot through the same SCHUNK tool changing system used by the other tools in the robotic system. Attaching the tool to its own tool-changing collar will greatly shorten the TCP distance between the nozzle and the end of the robot which will further increase the positional accuracy of the nozzle and the speed at which the robot can perform planar reorientations.

The tool will need to receive signals from the cabinet with a signal cable, but if the tool is fully integrated with the robot through the tool-changing system then it can be used in manufacturing processes with multiple tools. This project has opted to install a 19-strand cable and SCHUNK electrical tool changing modules that will carry all the necessary power and command signals from control cabinet to the microcontroller.

Initial experiments with the custom biopolymer materials found that the spatial printing system requires the flexibility to customise the size of the internal geometries of the hotend and extruder to fit the filament's non-standard sizes. Printing with larger and non-standard filament sizes is within the scope of this research, however the E3D hotends used in the first spatial printing system are not offered in sizes outside of 1.75mm and 3mm and cannot be modified to do so. Therefore, a hotend will be designed and build for the second extruder with variable sizes that cater specifically to the requirements of the custom co-extrusion materials.

A necessary improvement on the first spatial printing system is the maximum printing speed in free space. This has been limited by the rate at which the extrudate can be cooled at the tip of the nozzle, and despite upgrading the blower fan the maximum linear speed for the robot has not successfully exceeded 2mm/s. Printing at these speeds can be prohibitively time-consuming, as larger models can take at least a day to complete with no errors. To cool the extrusion faster a controllable supply of compressed air from the tool changing system will be used in place of the blower fan. This will be configured to supply an increased flow of air to a more precise region in front of the nozzle that will harden the material quicker, reduce the time the extrudate has to deflect while molten, and reduce the overall printing time.

Figure 42: Controllino MINI PLC (CONTROLLINO,2018)

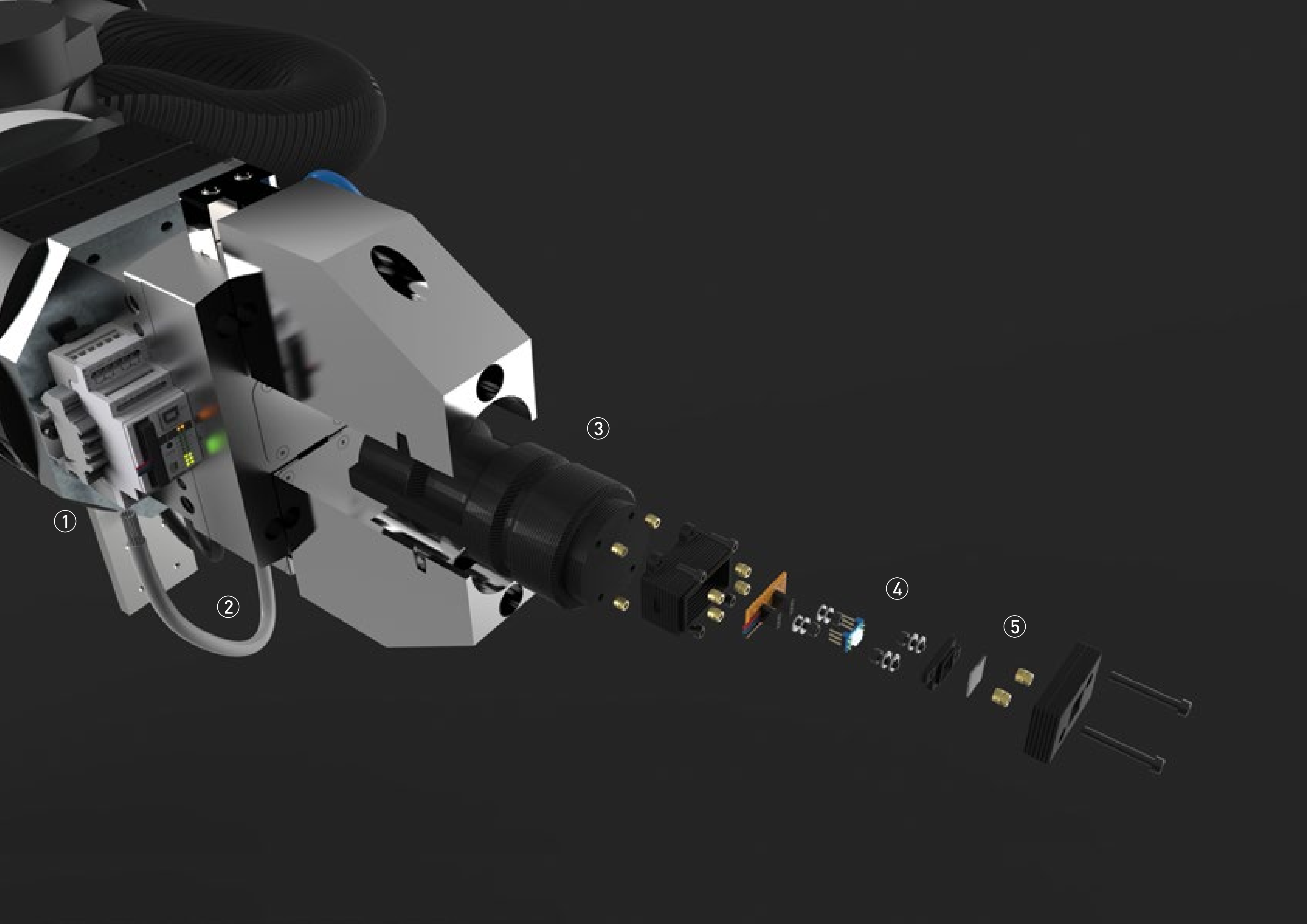
TESTING CONNECTIONS - LED TOOL

It is imperative that the logic controller selected to replace the Arduino and RAMPS 1.4 as a printing controller is determined to be capable of communicating with the ABB control cabinet before building another spatial printing tool. After a review of available PLCs, the Controllino MINI - an Arduino-based industrial microcontroller was selected for coding familiarity and its capability to receive 24V power and signals from the control cabinet. Arduino PLCs have a wide variety of proprietary code and downloadable libraries that can be used to interface with the electronic components of the tool, which will be selected based on their compatibility with the Controllino MINI, Arduino libraries, and control cabinet voltages.

As the components and behavior of the tool are not supported by any available 3D printing software, the code to run the extruder will be written from scratch in the Arduino IDE. At a basic level, the Controllino MINI will be programmed to continuously read a 0-10V signal and scale this number to speed in mm/min that will tell the extruder how fast to rotate. To test if this is possible, an RGB LED will emulate the extruders behaviour by changing colour in response to variations in the analog signal. Using an LED to test the communication system has the benefit that the changes are more apparent to the eye than the extruder and an LED is cheap and relatively easy to install. Once the code and connections are tested and functional using the LED they will be used as a base for the code that will run the spatial printing tool.

Tracking the changes of the LED as the robot's movement through space can be achieved using light painting. Photographing the robot with a long exposure in a darkened room captures the path of the LED as it moves through space, revealing the exact moment the signal makes a transition with a change in colour. These images can be used to ensure that the signal changes are synchronised with the robot's movements and also doubles as a visual preview of the printing process.

The following page documents an LED tool to fit the robot's pneumatic grippers that will be used to test the communication signals from the control cabinet. The tool will also be used to test design components for the spatial printing system to ensure that they are functional before use with the extrusion tool. As the LED requires red, green, and blue values to define a colour, the Controllino MINI will be configured to receive three analog signals from the control cabinet which will behave in the same manner as with the extruder.



TOOL DESIGN - LED TOOL

1 : CONTROLLINO MINI INDUSTRIAL ARDUINO PLC

The Controllino MINi is connected to the auxiliary robot cable and configured to receive three 0-10V analog inputs from the ABB control cabinet. The Arduino is programmed to continuously remap each of the 0-10V signals to 0-255 integer channels for the red, green, and blue channels of the RGB LED. This enables the user to select any colour in the RGB spectrum using a combination of voltages from the three analog signals in real-time

2 : AUXILIARY ROBOT CABLE

19 Strand OFLEX Robot Cable connected to SCHUNK electrical tool-changing module as illustrated in previous page. Used here to provide 24V power and analog signals to the Controllino MINI

3 : BOSS FOR PNEUMATIC GRIPPER

3D printed boss for the pneumatic gripper. Allows the LED assembly to be quickly installed on an existing robotic tool instead of developing a separate tool with duplicate tool changing and electronic equipment

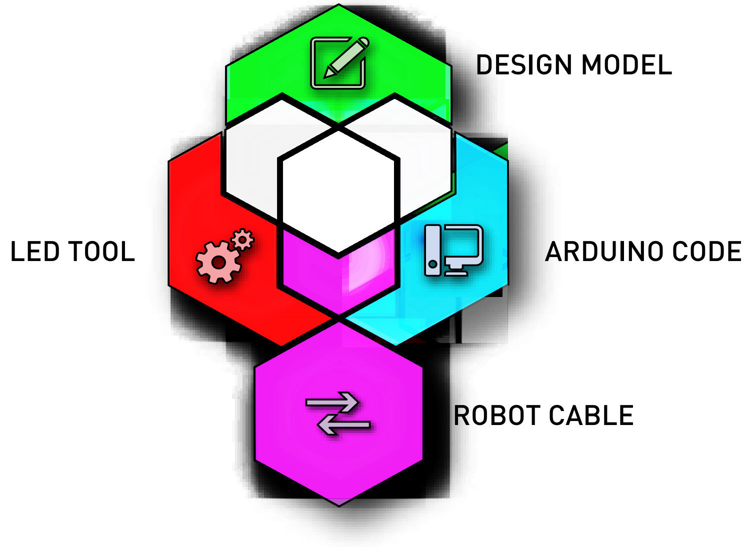
4 : ADAFRUIT DOTSTAR RGB LED

This addressable LED from Adafruit features 8-bit RGB display with selectable brightness and is compatible with the FastLED library for Arduino. Powered by the DotStar APA102 IC it has a fast 8MHz refresh rate which increases the resolution of the light painting images and responds to the changes sent by the control cabinet quickly. This is important as the movement speed of the robot can reach speeds in excess of meters per second and ensures that responses to the signal change from the cabinet stay aligned with the robot's movements. The LED uses both a clock and a data signal as well as 5V connections to the logic-level circuitry using the IDC socket

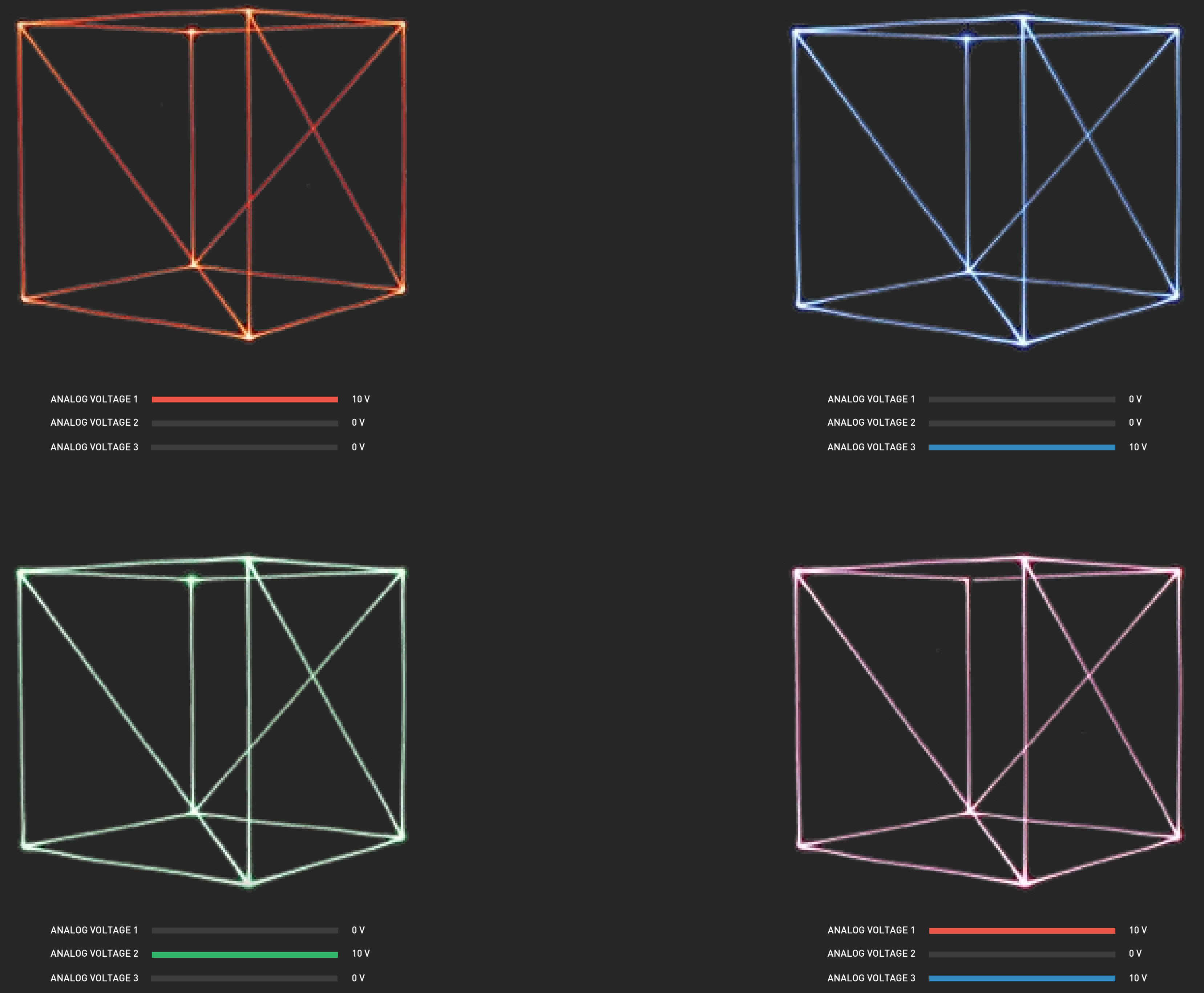
5 : FILTER HOUSING

Can create an array of lighting effects by housing combinations of different filters in front of the LED such as a diffusion filter and\or a light mask

The new microcontroller, LED hardware (used here to emulate the extruder behaviour), and the existing design model form the basis of the new spatial printing system, represented here with a new development diagram. The newly installed robot cable forms the bridge between the software and programming components of the project represented by the purple crossover node:



LED EXPERIMENTS



COMMUNICATION EXPERIMENTS

AIMS & OBJECTIVES

These experiments aim to establish the connections between the control cabinet and the Controllino MINI and use the LED tool to light paint previews of the design models.

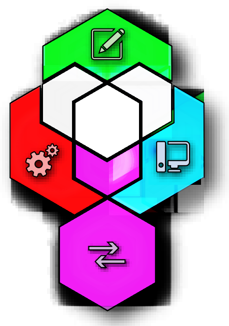
METHOD & VARIABLES

To meet the same level of communication as the first spatial printing system the robot must be able to move the tool tip to the printing substrate, turn on the extruder at a certain feedrate, move through the continuous line toolpath, and turn off the extruder at the end of movement. These experiments will test the workflow from the design model through the Arduino firmware to the tool's electronic components. In this case the LED tool will change colour in response to the analog signals the control cabinet sends as the robot moves through the toolpath, where each colour represents a different feedrate for the spatial printing tool.

PARAMETERS

DESIGN MODEL : 500mm Cube
ROBOT SPEED (MAX) : 4000 mm/s
TARGET ZONE : 1 mm

DEVELOPMENT DIAGRAM



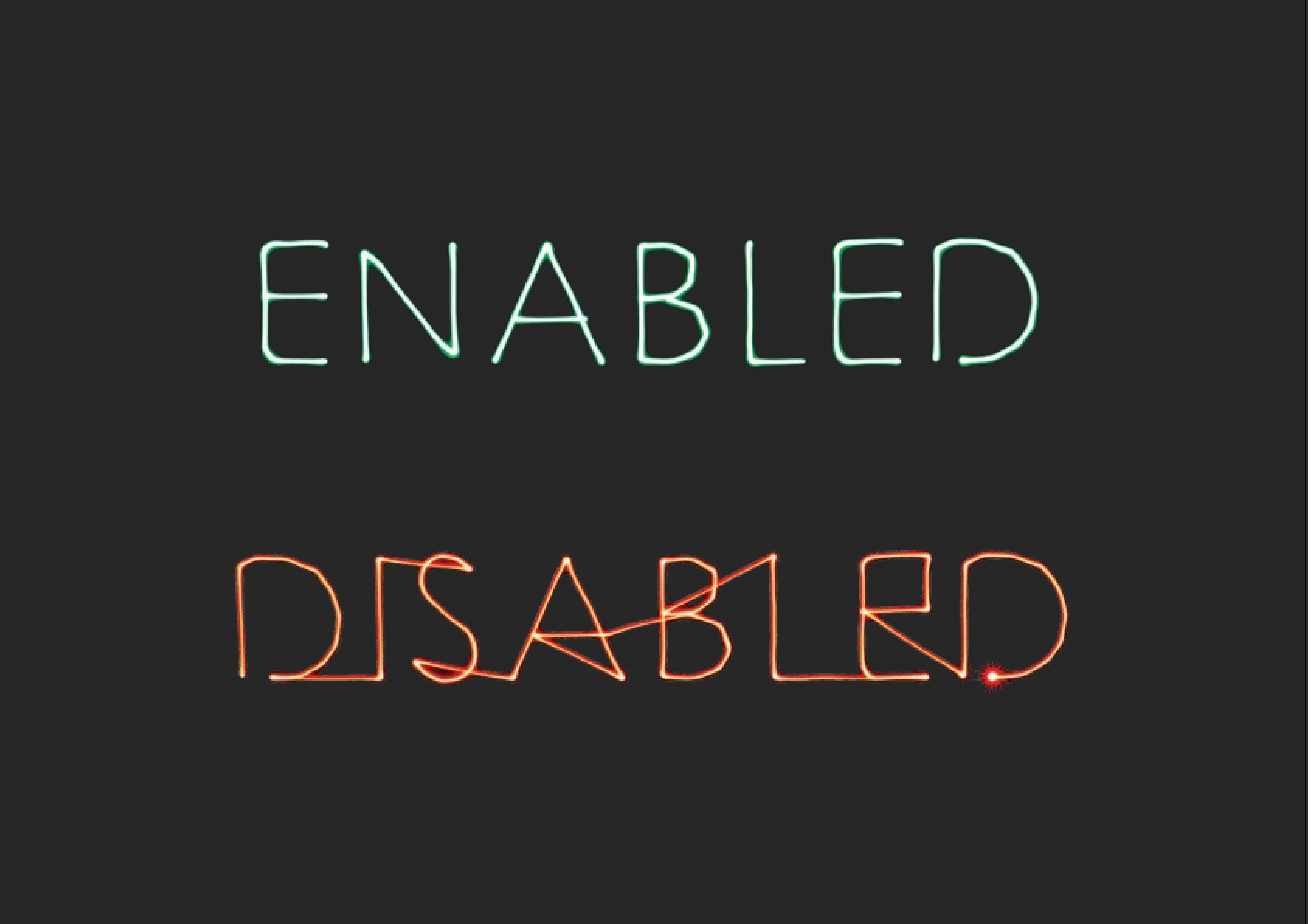
OBSERVATIONS

The Grasshopper workflow is proven capable of generating a robotic procedure in RAPID code using a basic continuous toolpath. The control cabinet processed this code and set the assigned analog voltages along the robot's movements as expected and the firmware that controls the LED was calibrated to the observed analog readings of the Controllino MINI. The brightness of the light was observed to intensify at the corners, indicating that the robot is performing accelerations as the TCP approaches each target. With a maximum robot speed of 4000mm/s this acceleration has a noticeable effect on the robot's movement, however at slower speeds such as those for spatial printing this acceleration is observed as much less intense.

CRITICAL REFLECTION

Arduino PLCs use an Analog-to-Digital-Converter (ADC) that read the analog signals from the control cabinet by comparing them to a reference voltage which in this case is the 24V supply voltage for the spatial printing tool. For an 8-bit (0-1023) ADC reading, the Controllino MINI is physically configured to use the supply voltage as the maximum reading (1023) limiting the maximum observed value of the 0-10V analog signals to 337. This is enough to remap each signal to the LED tool's integer channels which range from 0-255, but the signal has a tendency to fluctuate by an ADC value of 2 which is enough to slightly change the colour of the LED. This is not critical for the light painting experiments but may affect printing experiments where a fluctuating feedrate could deform the resulting extrusions.

HAL Robotics uses proprietary Grasshopper components to define attributes for the robot's movements such as the setting analog signals and robot speeds. Each attribute may be individually defined using HAL as shown here but cannot be defined parametrically, which is required for more advanced modelling where each movement has varying attributes that constantly change over the course of experimentation. Instead, much of the HAL system will be bypassed and replaced with Grasshopper scripts that assign attributes to each robotic movement based on design rules in the spatial printing model. HAL Robotics does not allow for assigning attributes in this way, so another Grasshopper script will handle RAPID code generation and HAL will be used solely for solving the inverse kinematics and collision detection for each movement.



TRAVEL MOVEMENT EXPERIMENTS

AIMS & OBJECTIVES

These experiments will test a Grasshopper system that disables the robot end-effector when moving between disconnected geometries

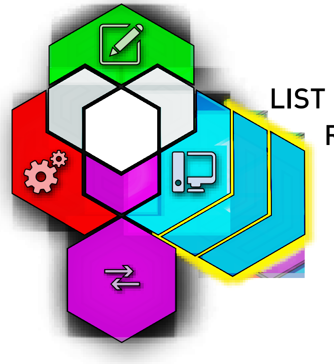
METHOD & VARIABLES

The design model has been updated with a script that assigns custom attributes to each robotic movement, and another script that generates the RAPID code used to command the robot. The model analyses each toolpath segment by feeding them through a series of conditional tests to discern whether they are extrusion movements or a travel movement that connects geometries together. The results are compiled into a dispatch pattern that is used to set custom parameters for the travel movements, such as setting the signal that controls the extruder to off and increasing the robot's speed. To illustrate this behaviour, a toolpathing font that creates text using single lines is fed into the design model and the travel movement filters are tested in both enabled and disabled modes.

PARAMETERS

DESIGN MODEL : Text Toolpaths
ROBOT SPEED (MAX) : 4000 mm/s
TARGET ZONE : 1 mm

DEVELOPMENT DIAGRAM



OBSERVATIONS

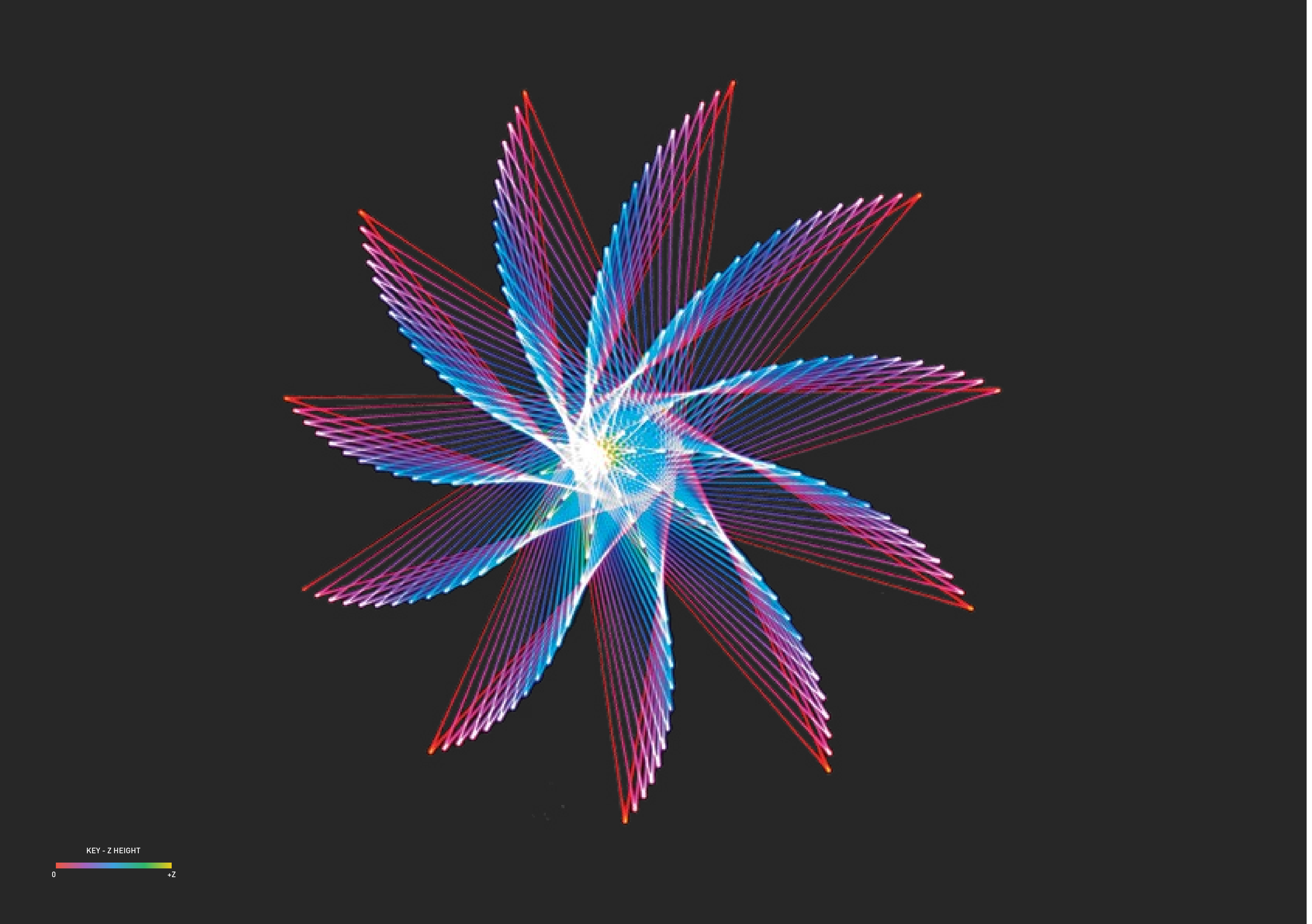
The travel movement dispatch system functioned as expected, switching the analog signals off between separate geometries. The timing of the analog signals is accurate with a minimal delay between the Arduino receiving the signals and sending the remapped voltages to the LED. The LED switches between on and off almost precisely as it reaches each target in space which is visible from lack of light bleeding into and out of the travel movements.

CRITICAL REFLECTION

The RAPID code generator was successfully implemented in these experiments and will replace the HAL Robotics components. From this point, HAL will only be used to calculate the inverse kinematics for the robot. The code generator essentially formats each toolpath into a select set of RAPID commands and declarations that automatically update based on the input geometry. This allows the system to be configured to use any RAPID commands the robot knows by simply formatting each command with parameters from the design model.

Assigning printing parameters to the robot's movements based on feature recognition allows the system to automatically detect the needs of each model and assign printing behaviour as required. This is demonstrated with the travel movement experiments here but can also be used to customise the robot's behaviour at various points in the model, such as after a vertical extrusion or during an extrusion on the substrate. This will be used in future testing in response to the results of materials experimentation.

The ability for the nozzle to travel without placing material greatly increases the complexity of the geometries that this system can print as the user can select precisely where material is deposited by the robot. This improves on the capabilities of in the first experimental section as the input geometries do not have to a single continuous line. Sections of each print can be designed with travel movements in between so that they do not collide with previously printed strands. The extruder's behaviour must be further tested using the spatial printing tool before full integration with the system and may require Arduino initiated retractions to prevent to nozzle from oozing while moving between geometries.



MULTIPLE SIGNAL EXPERIMENTS

AIMS & OBJECTIVES

This model will test using RAPID trigger commands to set multiple signals simultaneously.

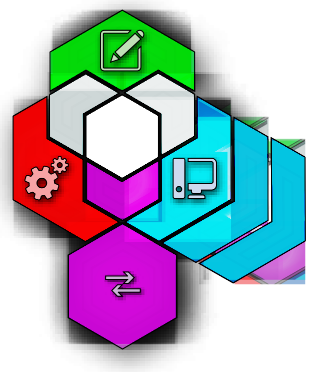
METHOD & VARIABLES

The RAPID code generation script from the previous experiment has been updated to use commands that can set multiple output signals with different values at defined points in the robot's movement. Each of the red, green, and blue channels for the LED have been assigned to an analog signal from the control cabinet so that combined they can select any colour in the RGB spectrum. The design input is a simple spirograph that gradually increases in height as it progresses from start to finish, represented here by a change in colour.

PARAMETERS

DESIGN MODEL : Spirograph
ROBOT SPEED (MAX) : 4000 mm/s
TARGET ZONE : 1 mm

DEVELOPMENT DIAGRAM

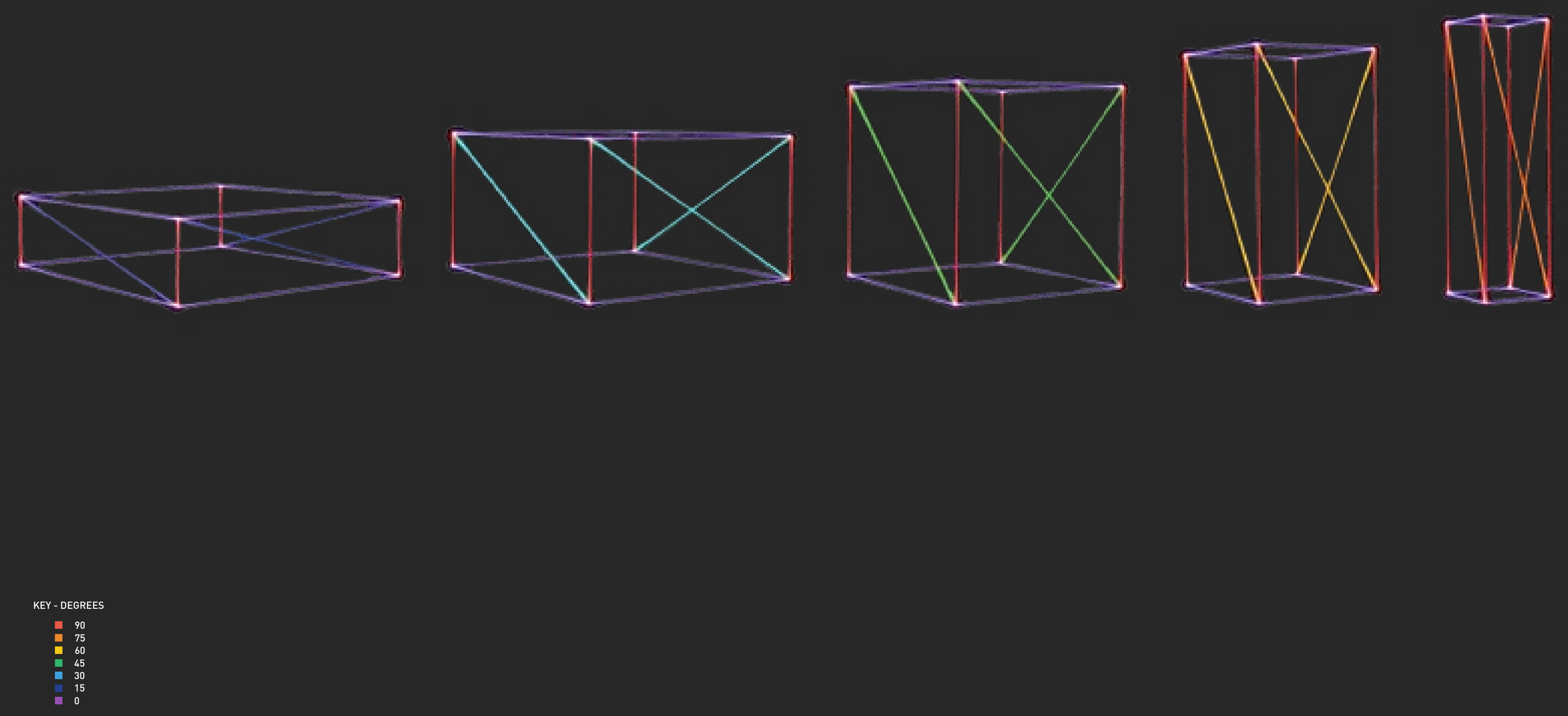


OBSERVATIONS

The toolpaths were observed to have a different colour as the Z-height of the model increased. From a bird's eye view the colours appeared to give depth to an otherwise two-dimensional image.

CRITICAL REFLECTION

The ability to simultaneously set several signals with their own individual values increases the amount of information that can be communicated between the control cabinet and the Controllino MINI. Each signal connected to the robot cable (and thus the colours of the LED) can be configured to make a change depending on a variable within the design system. Because the signals are disentangled they can be used to control different parts of the extrusion process, such as enabling the heater cartridges and increasing the rate of extrusion independent of each other. Using the LED tool, this allows the user to select certain colours or gradients to represent selected variables in the system so that the changes can be visualised.



FEEDRATE ADJUSTMENT EXPERIMENTS

AIMS & OBJECTIVES

These experiments will test a Grasshopper system that uses list operations to assign extrusion parameters to movements based on their vertical inclination.

METHOD & VARIABLES

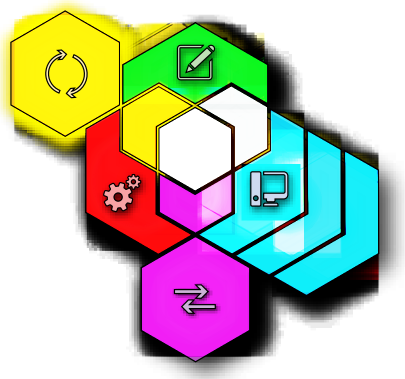
A component has been added to the design system that measures the vertical inclination of each line segment and sets the robot speed and extrusion rate for each different angle using a graph mapper. Each graph takes the standard robot and extrusion speeds and fits them to a graph that either increases or decreases each speed depending on if the extrusion direction is vertical, horizontal, downwards, or anywhere in-between. The graphs are user-customisable and will be tabulated from the results of material experimentation once the system is confirmed to communicate at this level. Another filter has also been integrated that separates printing movements on the substrate in much the same way as the previous experiments for which the speeds have been greatly increased. The LED tool has been programmed to display the each of these speeds in a different colour.

PARAMETERS

DESIGN MODEL : 200mm Hypotenuse Cubes
ROBOT SPEED (MAX) : 4000 mm/s
TARGET ZONE : 1 mm

DEVELOPMENT DIAGRAM

GRAPH MAPPER FEEDBACK



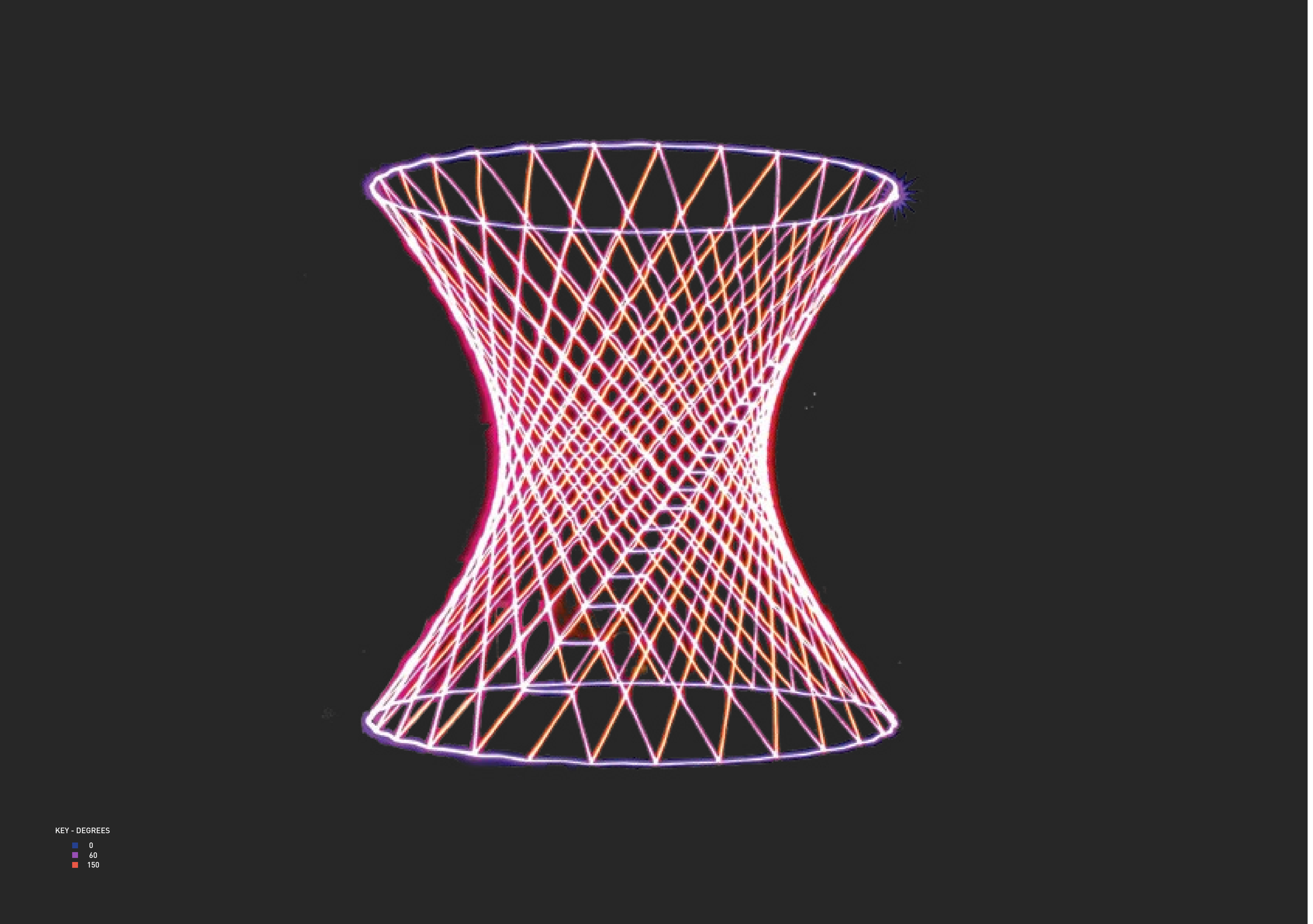
OBSERVATIONS

The toolpaths in each cube were observed to have different colours depending on their angular deflection from the Z axis. The bottom sections of each cube were also observed to be a specific colour.

CRITICAL REFLECTION

The graph mapping components and inclination filters were proven to function as intended and successfully selected between 7 different colours during movements with the LED tool. This has proven the system as a whole is capable of communicating at a level where the spatial printing tool can be assigned different parameters for each movement. Furthermore, the design model is structured so that the empirical results of experimentation can be fed directly into the graphs to account for a materials response to the system.

Integrating this component into the design model creates a feedback loop can be used to iteratively improve the spatial printing process for a selection of different materials. As such, it forms a link between the output of the hardware and the input of the design system represented by the orange node in the development diagram.



LED EXPERIMENTS - HYPERBOLOID

AIMS & OBJECTIVES

This experiment will test the LED toolpath preview with a geometrically-complex print model.

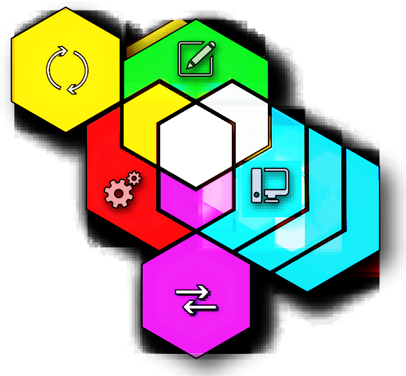
METHOD & VARIABLES

A hyperboloid surface has been designed in grasshopper and re-sequenced into a continuous toolpath that builds from the bottom up. This form will be used to test the design model to see if it responds to non-cubic inputs.

PARAMETERS

DESIGN MODEL : Hyperboloid
ROBOT SPEED (MAX) : 4000 mm/s
TARGET ZONE : 1 mm

DEVELOPMENT DIAGRAM

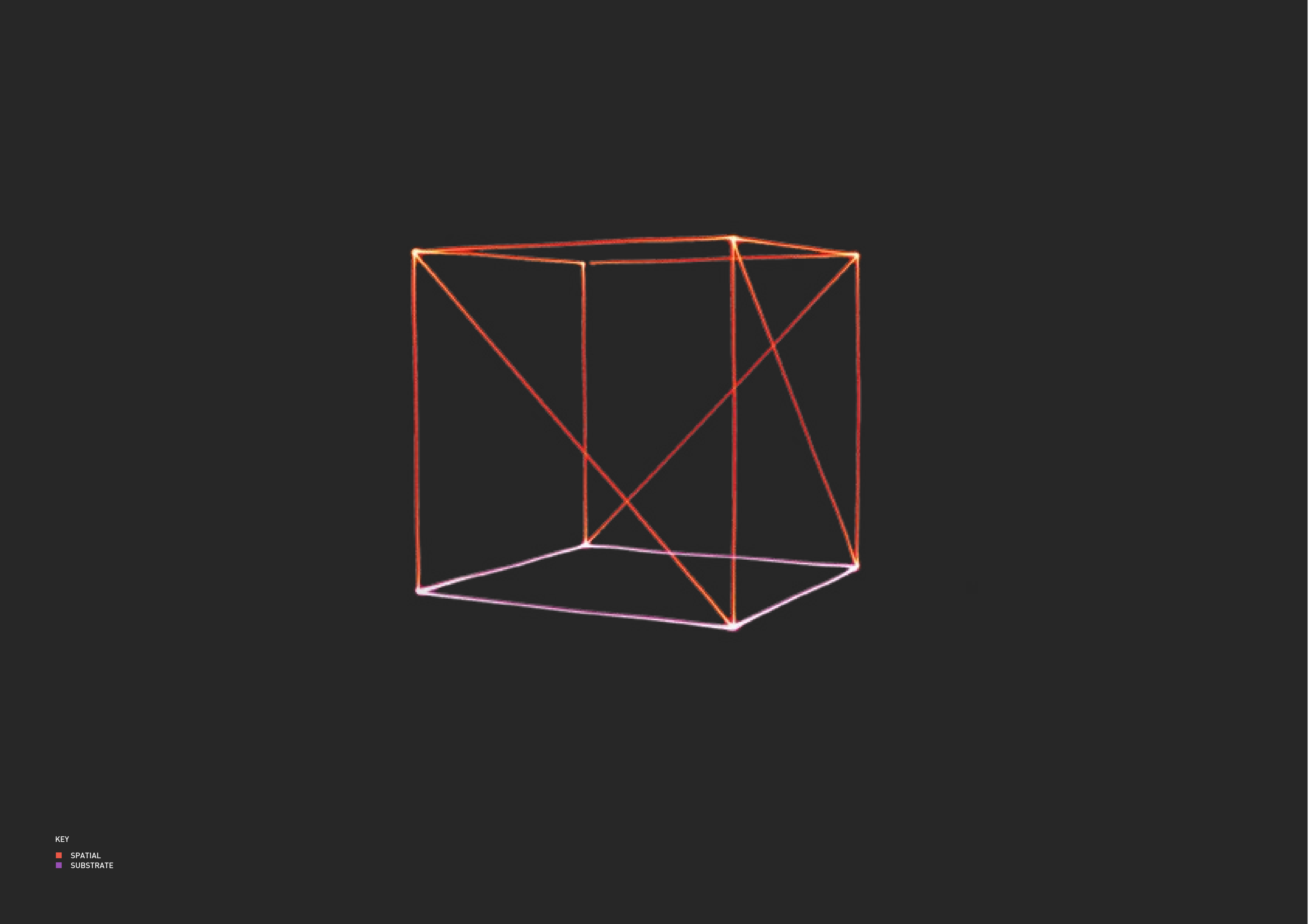


OBSERVATIONS

Each strand in the hyperboloid was observed to have a different colour based on its angular inclination from the print surface.

CRITICAL REFLECTION

A one-sheet hyperboloid contains a doubly-ruled surface that, when divided, contains only two sets of straight lines at set inclinations. A circular band joins the extrusions at the top and bottom of the model, resulting in a print model that only uses 4 different printing settings: substrate, angular inclines, angular declines, and 90-degree bridging movements. The design model was proven to function for this type of geometry, and the feed-rate changes based on angular inclination appear to be functional regardless of their direction in the XY plane.



SUBSTRATE FILTERING EXPERIMENT

AIMS & OBJECTIVES

These experiments will test another filter for the list operating system that assigns customs parameters for substrate printing movements.

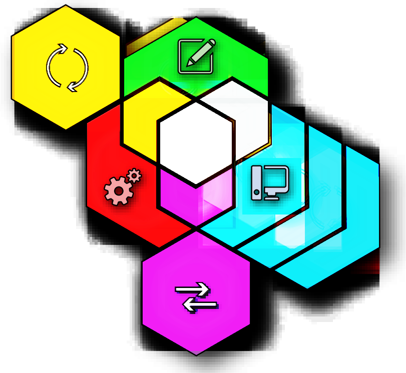
METHOD & VARIABLES

Using the same list operating system as the travel movement and feed-rate adjustment experiments in the previous section, another filter has been integrated that separates printing movements on the substrate. This experiment will assign substrate movements with a different colour to test if the filter operates as expected.

PARAMETERS

DESIGN MODEL : 200mm Cube
ROBOT SPEED (MAX) : 4000 mm/s
TARGET ZONE : 1 mm

DEVELOPMENT DIAGRAM

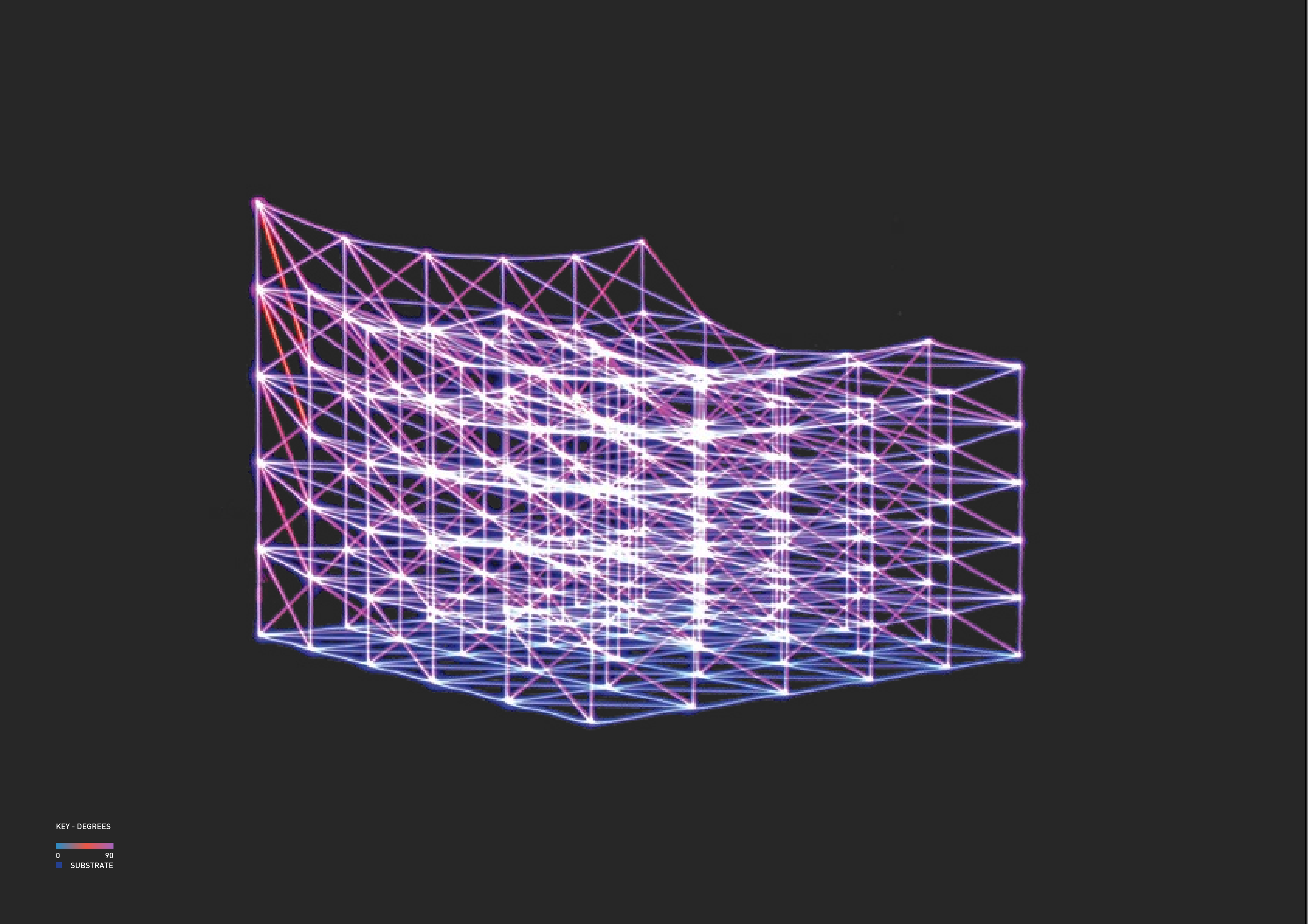


OBSERVATIONS

The toolpaths at the base of the model were observed to have different colours than the rest of the model that appeared to be unaffected by the modifiers applied by the other filters.

CRITICAL REFLECTION

The ability to set custom parameters for printing on the substrate should significantly increase the overall print time as the speed can be drastically increased without affecting the quality of the extrusion. Care must be taken to ensure that extrusions adhere well to the substrate as the model must often remain fixed for long periods of time. Printing on a substrate follows the same principals as FDM printing, so increasing the feed-rate will result in a wider extrusion which will increase the surface area of material in contact with the substrate. The maximum extrusion width will be limited by the flat section on the front of the nozzle and will be determined in the first material experiment with this system.



LED EXPERIMENTS - SPACE FRAME

AIMS & OBJECTIVES

This experiment will test an Arduino code that uses lookup tables to assign signals from the control cabinet to custom parameters.

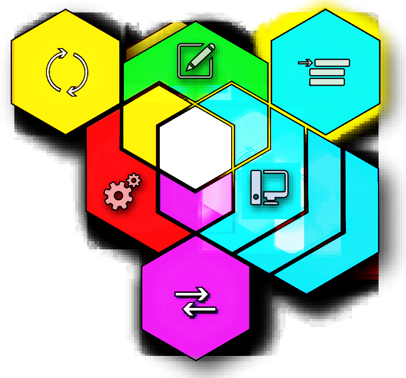
METHOD & VARIABLES

The Controllino MINI has been programmed to compare each signal to a list of pre-defined voltage values and retrieve a corresponding LED parameter by finding the voltage that the signal most closely matches.

PARAMETERS

DESIGN MODEL : 600mm x 600mm Space Frame
ROBOT SPEED (MAX) : 4000 mm/s
TARGET ZONE : 1 mm

DEVELOPMENT DIAGRAM



OBSERVATIONS

As in the previous experiment, the toolpaths in each cube were observed to have different colours depending on their angular deflection from the Z axis. The base of the model was also observed to be a specific colour.

CRITICAL REFLECTION

As the LED's colour changes in the same way as the previous experiment, this is proven to be an effective method of assigning any of the parameters programmed in the Arduino. Whilst this does not have any significant impact on programming the LED colours, the range of speeds that the stepper motor in the extruder is capable of is larger than the range of voltages of the analog signals use to select them. This system will be used to accurately select the extruder feed-rates, and together with the grasshopper component programmed to automatically update the Arduino code forms a programmatic link between the design model and the Arduino programming. This is represented by the teal link in the development diagram.

SPATIAL PRINTING SYSTEM II

EXTRUDER DESIGN - SELECTING COMPONENTS

Figure 43: Leadtek DM320T Digital Stepper Motor Driver (Leadtek, 2018)

Figure 44: SMC Compressed Air Regulator (SMC, 2018)

Figure 45: E3D PT100 Thermocouple & Amplifier (E3D, 2018)

Figure 46: 24V Heater Cartridge (E3D, 2018)

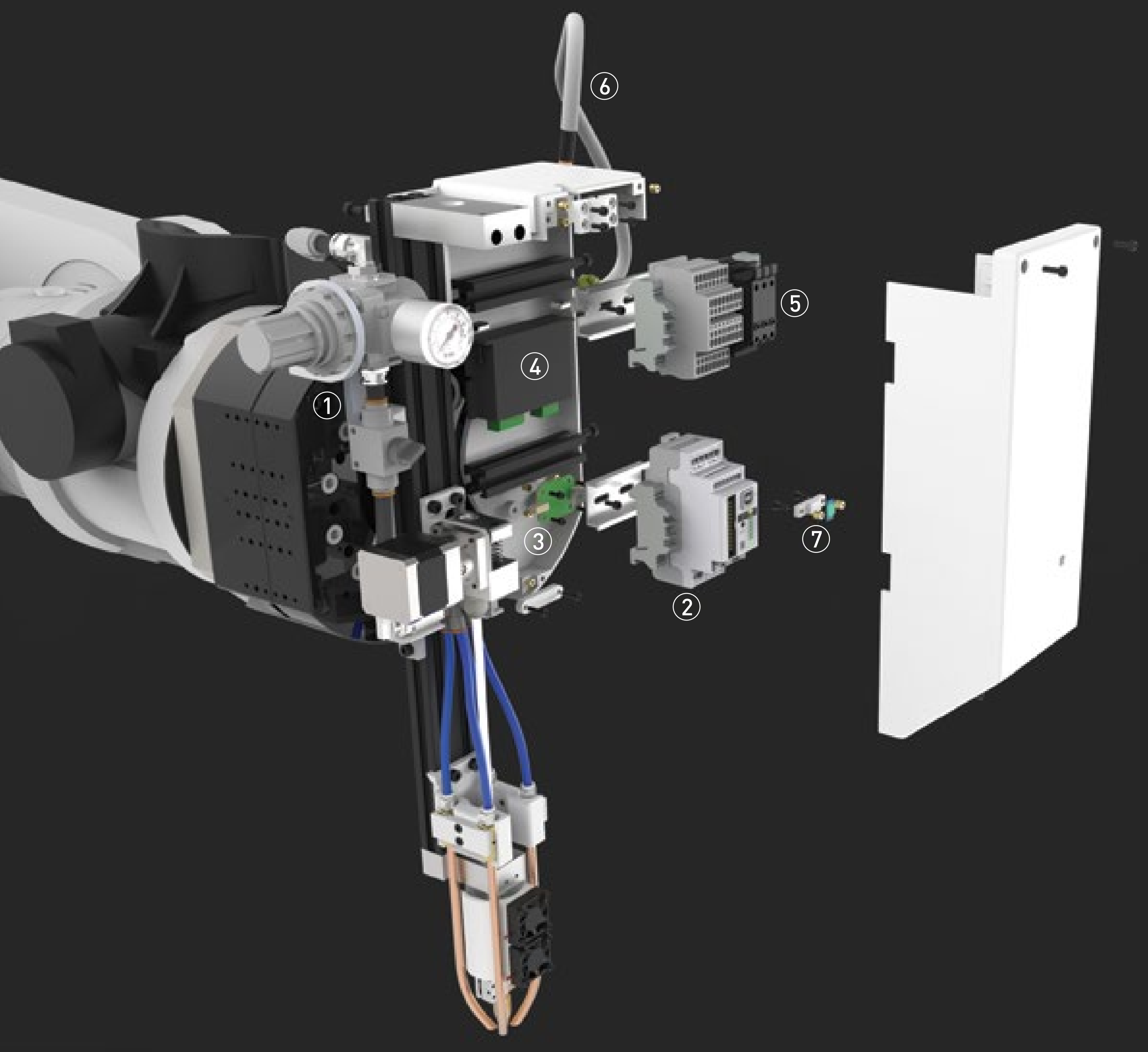
Figure 47: Adafruit NeoPixel SK6812 5050 LED (Adafruit, 2018)

Now that the Controllino MINI is proven function with the robot control cabinet, the remaining componentry for the spatial printing system will be selected based on their compatibility with the Controllino MINI, Arduino libraries, and control cabinet voltages. For example, the Leadtek DM302 digital stepper motor driver selected to power the stepper motor is controlled using three digital outputs from the Controllino MINI's logic-level circuitry, powered by a 24V supply rail from the control cabinet, and programmed using the AccelStepper library available for Arduino.

The spatial printing tool needs to reproducible within the workshop at VUW in a range of different sizes for experimenting with non-standard filaments. The extruder setup from the first spatial printing tool will be remodelled to fit the new extruder configuration as it is capable of feeding up to 6mm filaments which is within the scope of this research. However, the hotend and the PTFE feed line from the extruder must be modified for each significant size variation. To support this the extruder and hotend have been designed to interchange between parametrically generated sets of heat-breaks, nozzles, and extruder inserts to fit a selection of commercially available PTFE liners and pneumatic fittings. The hotend will use the same electronic componentry as the E3D v6 used in the first spatial printing system because the amplified PT100 thermocouple is compatible with the Controllino MINI and the heater cartridge operates at the same voltage as the control cabinet. The hotend's heater block will feature a second heater cartridge that can be enabled to account for the increased material throughput of larger filament sizes, and two fans to account for the increased heat radiation away from the hotend.

Because this configuration does not include an LCD readout or a G-code response to indicate the status of the extruder the tool will use an LED to display the progress of preheating operations and extruder movements visually. For this task, an Adafruit NeoPixel RGB Led was selected as it can be run from the Controllino MINI's 5V regulator and uses only one of a limited number of digital output pins to display a complete range of RGB colours. The behaviour of the LED will be programmed using the FastLED Arduino library to turn blue while idling, flash and change colour during a preheat and turn solid green when the spatial printing tool is ready to extrude.

The compressed air will cool the extrusion at the tip of the hotend by way of a combination of standard HVAC fittings, SMC pneumatic fittings and an SMC regulator that can be used to control the intensity of the cooling jets. The regulated air feed will split into separate lines where they are then adapted to connect to copper HVAC tubing so that it can be shaped to point directly in front of the nozzle from opposite angles. Sections of the tubing are flexible enough to allow for the fine adjustment of the jet's placement, and the components are rated to withstand the 120psi pressure of the workshop's compressed air supply.



TOOL DESIGN - PNEUMATICS & ELECTRONICS

1 : SMC COMPRESSED AIR REGULATOR AND VALVE

The compressed air from the robot's cooling supply line is used to feed the cooling jets at the tip of the extruder. The pressure of the air can be adjusted to suit the material by closing the valve so that the gauge can read and manually adjusting the regulator

2 : CONTROLLINO MINI INDUSTRIAL ARDUINO PLC

The Controllino MINI is connected to the auxiliary robot cable and configured to receive two 0-10V analog signals and two 24V digital signals from the ABB control cabinet. The Arduino is programmed to use the digital signals to switch on and off the extruder heating system and to enable the extruder, and the analog signals are remapped to control the temperature and rate of extrusion in real time in the same manner as the LED tool

3 : PT100 THERMOCOUPLE AMPLIFIER

Used to amplify the signal from the thermocouple in the E3D hotend to a 5V signal that the Arduino can read. Connects through the PLC socket into the Arduino's logic level circuitry

4 : DIGITAL STEPPER MOTOR DRIVER

The stepper motor for the extruder is powered by this Leadshine DM320T digital stepper motor driver which operates on a 24V power supply and is controlled by two digital signals from the Arduino's logic-level circuitry through the IDC socket. The stepper driver has multiple different microstepping settings that can be changed to modify the resolution of the stepper movements for more precise extrusion

5 : PHOENIX TERMINAL BLOCKS AND FUSE HOLDERS

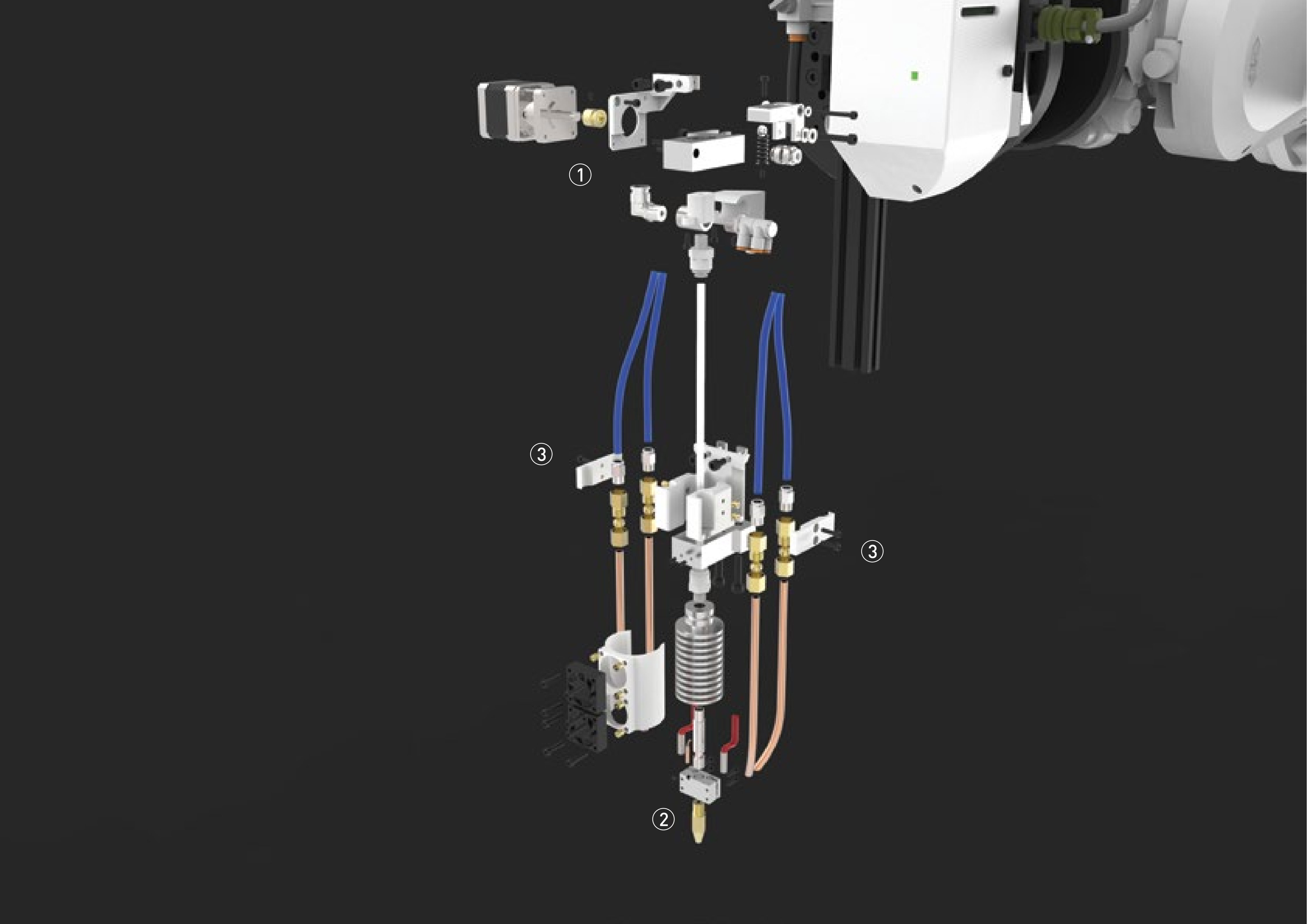
Electrical connections for the spatial printing tool. Terminal blocks are installed here and in the control cabinet so that the cabling configurations can be modified for the needs of further printing experiments and other tools. The terminal blocks are double-level to save space on the printing tool, and the fuses are installed as a failsafe for the supply lines to ensure the maximum amperage of the auxiliary robot cables are not exceeded

6 : AUXILIARY ROBOT CABLE

19 Strand OFLEX Robot Cable connected to SCHUNK electrical tool-changing module as demonstrated with the LED Light Painting Tool. The system has been configured to provide 24V power with multiple analog and digital signals to the Controllino MINI as well as a return digital signal to the control cabinet to indicate the pre-heating process is complete. Components with a large current draw such as heater cartridges, stepper motor driver, and cooling fans each have a separate 24V rail to keep within the maximum amperage of the individual strands of cable

7 : ADAFRUIT NEOPIXEL RGB LED

Similar to the DotStar APA102, this addressable LED from Adafruit features 8-bit RGB display with selectable brightness and is compatible with the FastLED library for Arduino. The refresh rate of the NeoPixel SK6812 IC is not as fast as the DotStar used in the LED Light Painting Tool but only requires one digital signal to operate which is necessary for the number of outputs available on the Controllino MINI. The LED is programmed to change colour indicating the status of the heating and extrusion systems of the spatial printing tool as a form of visual feedback



TOOL DESIGN - EXTRUDER & HOTEND

1 : BOWDEN-STYLE EXTRUDER ASSEMBLY

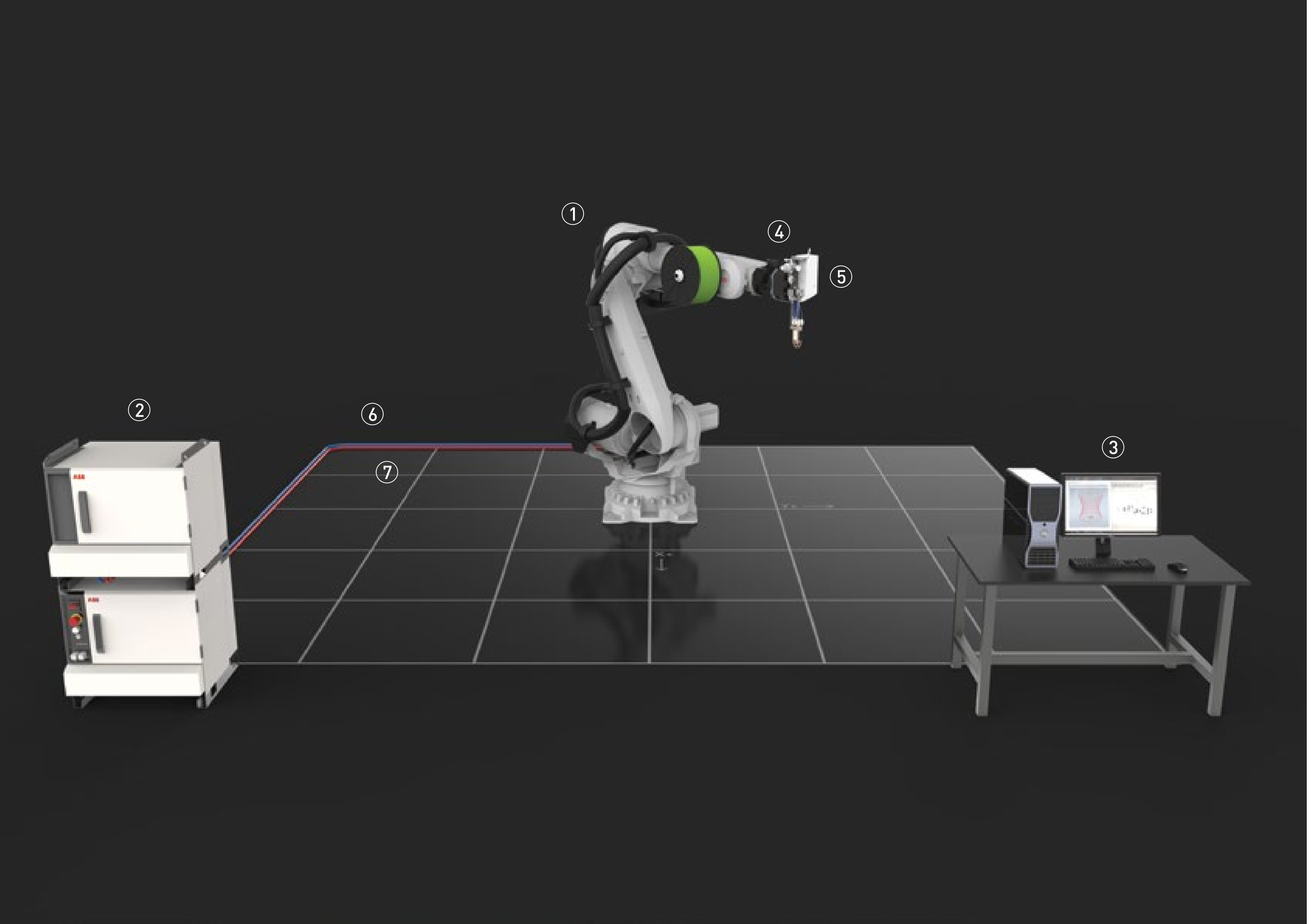
Similiar to the first spatial printing tool, this extruder consists of two main sections; a high-torque geared stepper motor with a brass pinch gear and an idler arm with a bearing compressed by a spring. The bearing on the idler arm presses the filament into the pinch gear forcing it into a PTFE liner tube that feeds the hotend. The extruder can fit a range of filament sizes and the PTFE liner is housed in a removeable 3D printed insert to make changing between filament sizes easier. The digital model for these inserts parametricaly accounts for the changing PTFE lining size, accompanying pneumatic fitting, and the varying distance between the extruder's pinch gear and the edge of the filament

2 : DUAL HEATER HOTEND

The Bowden-style hotend designed for this spatial printing system is made to be configured with an interchangeable set of core components that adapts the tool to print with filaments up to 5.5mm in diameter. The brass nozzle and heatbreak are parametrically designed to be made in a range of different sizes that fit within the heatsink and heater block and adapt to the dimensions of available PTFE lining sizes and accompanying pneumatic fittings. The heater block also houses two 24V heater cartridges for the higher material throughput of larger filaments as well as a PT100 thermocouple that the Arduino uses to read the temperature of the hotend. The heating process is controlled using a PID algorithm programmed in Arduino which has been calibrated for this specific hardware setup, and two cooling fans are attached to the heatsink to keep the heat confined to the heater block and nozzle

3 : COMPRESSED AIR COOLING JETS

The cooling jets are connected to the robot arm's compressed air cooling supply line that are regulated through the SMC components illustrated on the precious page. The supply line is split into 4 separate flexible tubes that are each attached to a copper HVAC refrigeration tube through a series of fittings. The tips of these tubes are precisely located to cool the molten extrusions as soon as they exit the tip of the nozzle so that material can be placed in free space. The tubing and fittings are clamped within a 3D printed housing that can be adjusted to precisely locate the cooling jets so that they only cool the molten extrusion after it has exited the nozzle



ROBOTIC SYSTEM

The spatial printing tool has a number of interfaces within the robotic system which are illustrated in the diagram opposite:

1 : ABB IRB6700 INDUSTRIAL ROBOT ARM

This six-axis robot arm serves as the base of all movement for the spatial printing tool and is controlled by the ABB IRC5 Control Cabinet

2 : IRC5 CONTROL CABINET

The control cabinet is the processing heart of the robot arm and controls all of the robot's motion and input output signals. The cabinet has been equipped with an auxiliary robot cable (see below) that connects to the user-programmable analog and digital modules for communicating with the spatial printing tool. Programs are uploaded to the control cabinet using the touch pendant via USB or from a host computer via ethernet

3 : CONTROL COMPUTER

The computer is used for 3D modelling and programming robotic processes as well as coding the Arduino firmware. The programs installed on this computer are noted in the Software and Design Environment Overview

4 : SCHUNK TOOL CHANGING SYSTEM

Pneumatic tool changing system for the robot that allows the user to quickly switch between tools and use multiple tools within a manufacturing process. The tool changer is configured with electronic tool changing modules that automatically make the electronics connections with the Arduino when the spatial printing tool is equipped

5 : SPATIAL PRINTING TOOL V2

The second spatial printing end effector as illustrated in the extruder breakdown documentation. Compared to the first spatial printing tool it has an improved form factor with a much shorter tool length improving the positional accuracy of the extruder's tip and the speed of planar reorientation movements

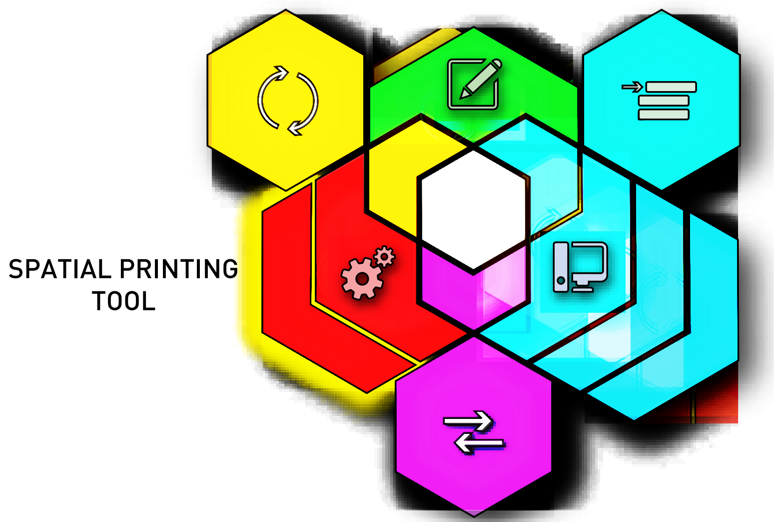
6 : ROBOT CONTROL CABLES

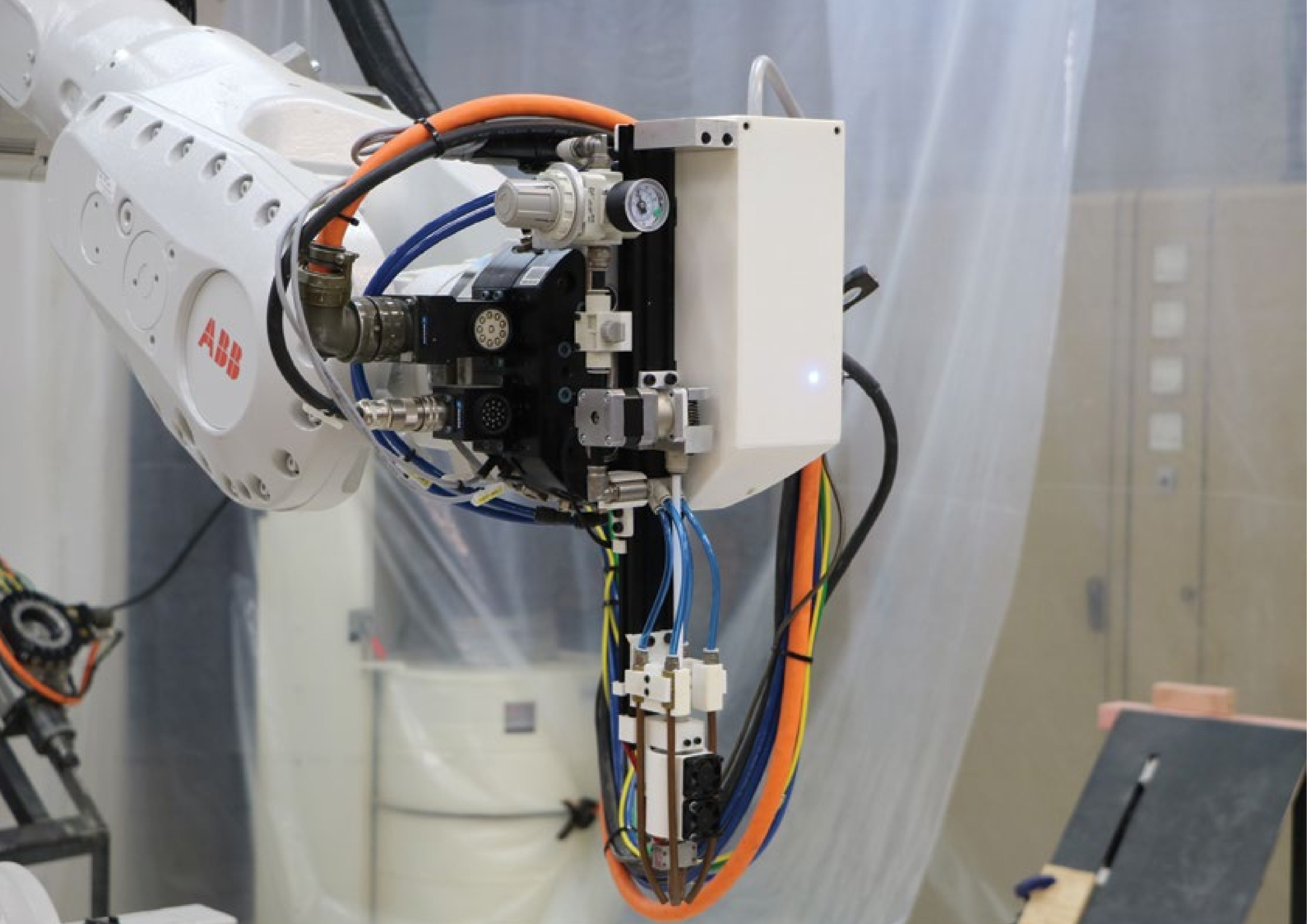
Cabling from the IRC5 Control Cabinet to carry all of the power and signals for the robot's movements and tools, represented here as a blue cable. Has a limited number of digital signals used for existing tools that can be purposed for communicating with the spatial printing tool

7 : AUXILIARY ROBOT CABLE

19 Strand OFLEX Robot Cable that connects the ABB Control Cabinet to the SCHUNK electrical tool-changing module as illustrated in the extruder design documentation. The cable is wired to a terminal block in the control cabinet where it is connected to the 24V supply voltages and analog and digital signal modules used to power and communicate with the spatial printing tool

The new spatial printing tool is added here as another hardware extention of the spatial printing system. The Arduino code developed for the spatial printing tool and the grasshopper design model form the basis of the new spatial printing system at the core of the Venn Development Diagram:

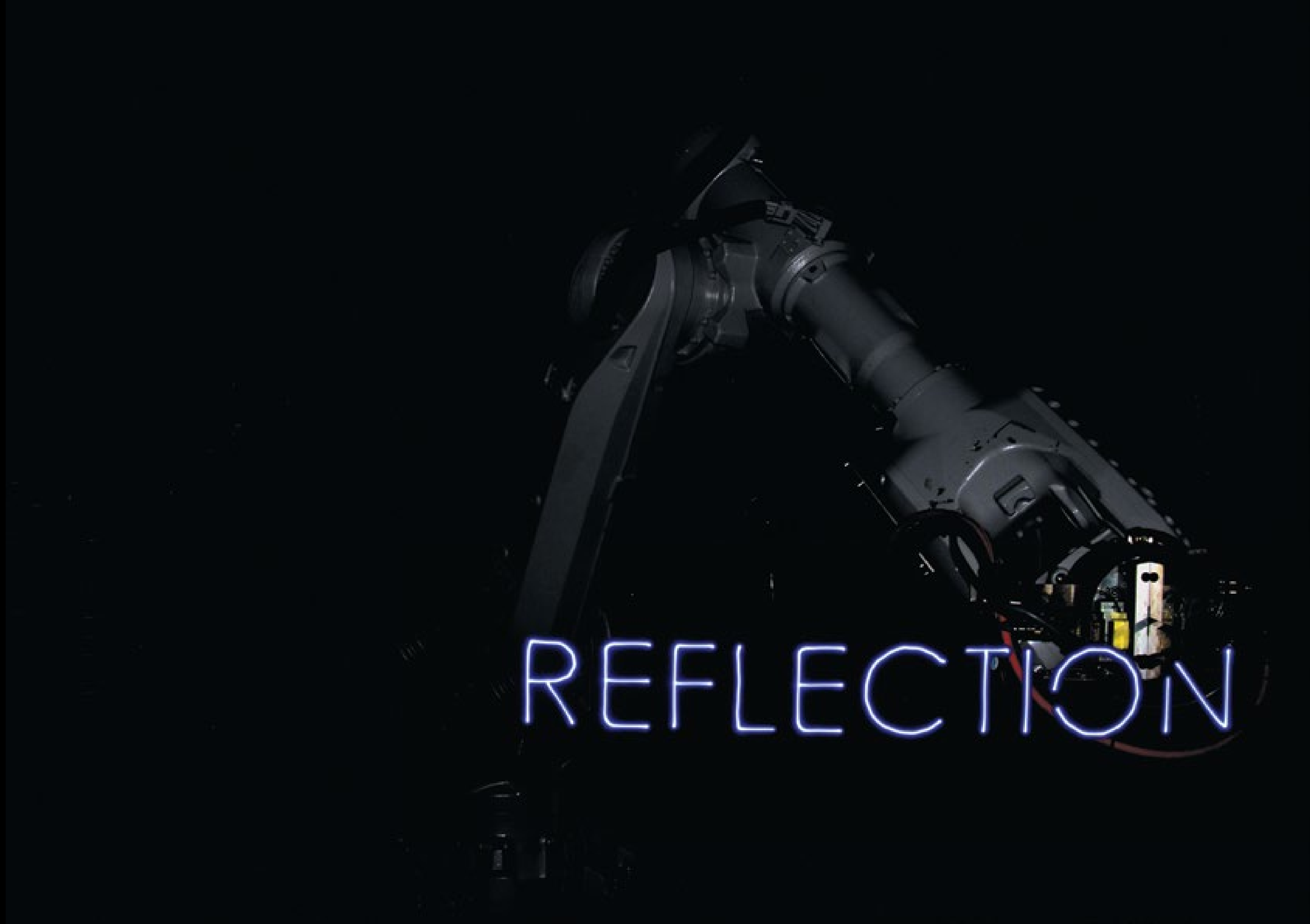




ROBOTIC SYSTEM - DISCUSSION

The spatial printing tool has been assembled and tested using the Arduino code. During initial testing, it has been proven that the robot cabinet can control the extrusion rate, temperature, and cooling in alignment with the robot's movements, and can switch on and off both the heating and extrusion processes using digital signals. The robot and Arduino have also been programmed to wait for the heating process to complete before proceeding with the printing process by reading a digital signal in the control cabinet sent by the Controllino MINI once the spatial printing tool is ready. ProHT material has been successfully extruded using the spatial printing tool, and the pneumatic cooling jets are capable of freezing the extrudate immediately after leaving the nozzle.

Due to restrictions in time and limited access to the robot, the LED experiments stand in place of material experiments with the second spatial printing tool as proof of successful communication and programming. The digital model in grasshopper used to interpret input forms and generate the RAPID and Arduino code to control the robot and extruder have been successfully tested using a variety of different models. The programming of the spatial printing tool has also been successfully tested sending and receiving commands with the control cabinet. Altogether the system is fully capable of automated spatial printing, with a variety of parameters that users can change in response to the results of experimentation. The system is discussed further in the Reflections chapter, and further documentation can be found in the appendices.


REFLECTION

OVERVIEW

This research developed a rigorous system for improving the craft qualities of printed geometries. It adjusts the printing parameters of input designs by directly using the results of material experiments in a feedback loop. The system was iteratively improved by printing a selection of spatially-defined structures and responding to desirable craft qualities found in each experiment. By providing a method of printing self-supporting structures spatially, this system offers opportunities for associated research to fabricate novel artefacts with increasingly complex geometries.

Precedents discovered in the background research helped narrow down the technical criteria for a successful spatial printing system, and provided a window into the process of developing new approaches to additive manufacturing. The decision to create the first system using existing open-source extrusion parts made for a quick build that led to a focus on materials experimentation early in the project. This system could print structures spatially using biopolymers extruded in a single continuous toolpath. Various design methods were implemented to adapt the printing process to the model, and the model to the printing process. Each had an effect of improving the printing quality and mechanical properties of printed structures. Ultimately, the first system was capable of printing spatial structures with desirable craft qualities, but it was not able to adapt to the needs of Scion's co-extrusion filaments, and it lacked communication with the robot's control cabinet.

Using the knowledge gained from the first round of experiments to build a new spatial printing system helped this project to overcome many of the challenges presented. After experimenting with new methods of robotic control and communication, another system was built that can assign different printing parameters to each part of the model, and can adapt the printing process to the needs of the materials and design model inputs. The hardware for the new tool was parametrically designed to be made in-house at the university workshop for a range of different filament sizes, including for the particular needs of Scion's experimental co-extrusion materials.

The workflow designed for this spatial printing system runs continuously from input to output. It uses a feedback loop to respond to the needs of the material and the input model. At the most basic level it can be used as an automated spatial printing calculator, taking any number of polyline inputs and generating all the necessary code required to spatially print those models as well as a coloured LED toolpath preview. At a more in-depth level the workflow is a fully-customisable experimental workbench that can be configured to a range of hardware settings, material parameters, and robotic commands.

This research illustrates the intricate relationships between material and process whereby the user is an informed mediator between design and form. Despite the level of automation and control, the spatial printing system does not seek to simply produce any design input by the user but rather acts as an informed depositor of material in space. Designing a spatial printing toolpath requires careful consideration of structure whilst avoiding potential collisions with previously printed geometries. Integrating the material responses to the system into the design model alleviates the need for the user to simultaneously design for the requirements of both the materials and the structure. As a result, this system can afford the user a level of freedom in the complexity of artefacts they can create with increased design complexity, placing material only where it is required.

LIMITATIONS

TECHNICAL LIMITATIONS

The system built for this research was designed to be versatile so that it can adapt to a variety of materials, filament sizes, robotic movements, and input forms. Although the system can automatically generate necessary parameters and machine code for materials and components calibrated to the system, it does not yet lend itself as a fully-automated spatial printing process. Therefore, the system's primary limitation is that it remains a research tool for in-depth material and process experimentation and requires a user who is adequately informed about the relationships between each element within the system.

The communication protocols established between the control cabinet and the Controllino MINI for both the spatial printing tool and LED tool is capable of triggering pre-programmed behaviours in time with the robot's movements at near-instantaneous speed. However, this version of the Controllino PLC does not come with a separate voltage divider for reading analog signals from 0-10V but instead interprets the signals based on a 0-24V scale This reduces the maximum resolution of the signals to a measured 337 out of a possible 1024 bits. Together, with a slight fluctuation in the analog signal, the number of values the Controllino can accurately read from a lookup table is limited to approximately 40. This cap does not affect the LED tool as the signals remap between 0-255 for each colour channel, but if the spatial printing tool must use a feed-rate that is not already in the lookup table, then the firmware must be updated with new values. A component in grasshopper has been programmed to output a lookup table for each experiment automatically, and a USB connection between the control computer and the printing tool is used to update the firmware as needed. Even so, this extra step in the process can be a hindrance for experiments with constantly changing feed-rates.

The extruder and hotend were designed with an interchangeable core so that components with different internal geometries can be fitted to cater to Scion's coextrusion filaments in non-standard sizes. A method of cutting the long fibres in these filaments has not yet been developed and must be extruded along a continuous toolpath much like the experiments using the first spatial printing tool

RESEARCH LIMITATIONS

The selection of outputs and applications of this system were influenced by many factors. Previously discussed technical and computational limitations, as well as material complications, had a large effect on the direction of this project. Navigating the possible pathways this research could take required a constant consideration of limitations as they presented themselves.

The most prevalent factor in designing the system and running experiments was robot time. The size and number of prints were largely confined by the length of time they took to complete, and whether each could fit within allotted sessions in the robot's schedule. This made increasing the system's print speed of paramount importance as many of the prints to test large-scale applications of the system were projected to take a number of days. Testing the communication protocols and the system's response to various input design models was performed largely with the LED tool due to the comparatively short time required to complete each experiment.

The purpose of developing a versatile spatial printing system is to harness desirable craft qualities that arise from the results of experimentation. Materials with workable spatial printing properties were discovered, and the system was calibrated to evoke as much of their native qualities as possible. The system could only elicit desirable properties from a material to a point where further progress required tuning the materials themselves, which is beyond the scope of this research. Co-development of hardware, design model and materials could further improve the craft qualities of artefacts generated by this system.

Each print model documented in this research was designed to test a particular material response or aspect of the spatial printing system using a rigorous experimental process. Now that the workflow has been refined to accept a range of linear toolpath inputs, one of the remaining thresholds is a substantial increase in the complexity of input design models. This may include designing prints with large overhangs, an increased range of movement, or the integration of Finite Element Analysis as previously described, which is a departure from the research methods and objectives for this research.

FURTHER RESEARCH

FURTHER DEVELOPMENTS

Research into further novel and complex spatial printing techniques will require a largely technical approach. As demonstrated in the experimentation sections in this research, opportunities to entreat desirable qualities of the materials depends largely on the capabilities of the spatial printing system. The design model, communication protocols, Arduino and robot coding, and printing hardware generated by this research serves as an entirely flexible platform for further developments into each of these aspects of the system, which may include;

- Material research - testing the system with an expanded array of standard and experimental FDM filaments may uncover materials that can be printed spatially with new and desirable craft qualities.

- Incorporation of the spatial printing tool into multi-material and multi-process manufacture could yield entirely new applications for additive manufacture and improve on the resulting craft qualities of output artefacts

- Integration of Finite Element Analysis (FEA) into the system could provide structural justifications for print models with an increased focus on the sustainable use of materials, and a valuable feedback component for the printing process.

- Development of an intuitive design workflow that helps the user create more complex spatial printing movements with less focus on technical interactions within the system.

- Further adaption of the system to print with co-extrusion filaments, and exploration of novel spatially printed structures with a focus on tensile properties.

- Exploration of multi-material prints to diversify the craft qualities of spatially printed artefacts

- Integration of further FDM techniques to improve on craft qualities of printed structures, such as extruder retractions and accelerations.

APPLICATIONS

Spatial printing in the manner illustrated in this research remains largely confined to design and construction research and does not yet lend itself as a refined and inclusive method of manufacture such as rapid prototyping. Potential spatial printing approaches were explored in this research as a method of verifying the ability for the system to respond holistically to a variety of design inputs and materials. The applications of this system range far broader than the scope of this research, however the underpinning techniques, technical process, and material responses documented here could lend the spatial printing to a selection of appropriate uses, such as:

- Furniture; The strong mechanical properties of printed geometries and the maximum build volume of the system are ideal for experimenting with the creation of full-scale furniture pieces.

- Construction; Use of the system to create large-scale complex space-frames for concrete formwork and multi-material insulative framing.

- Film Sets & Props; Printing of large-scale topological structures and artefacts as a foundation for building film sets using sustainable materials.

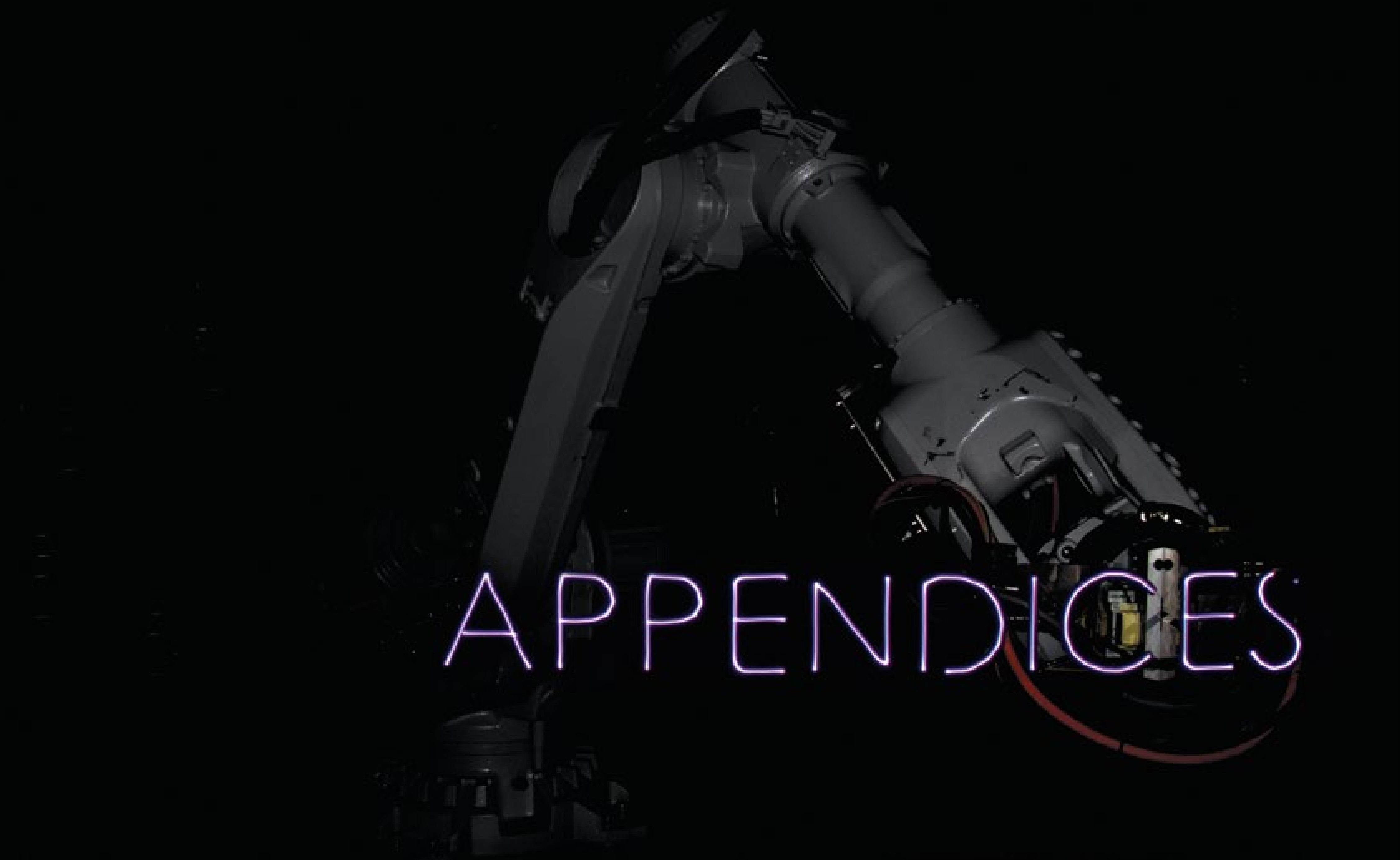
- Lighting; Complexity in material placement can be used to explore light and shadow through lattices of strands and patterned surfaces.

- Biomimetic Structures; The compatibility of the design model with a range of other grasshopper components and design strategies opens up possibility for integrating biomimetic design drivers, such as evolutionary systems and L-systems.

CONCLUSION

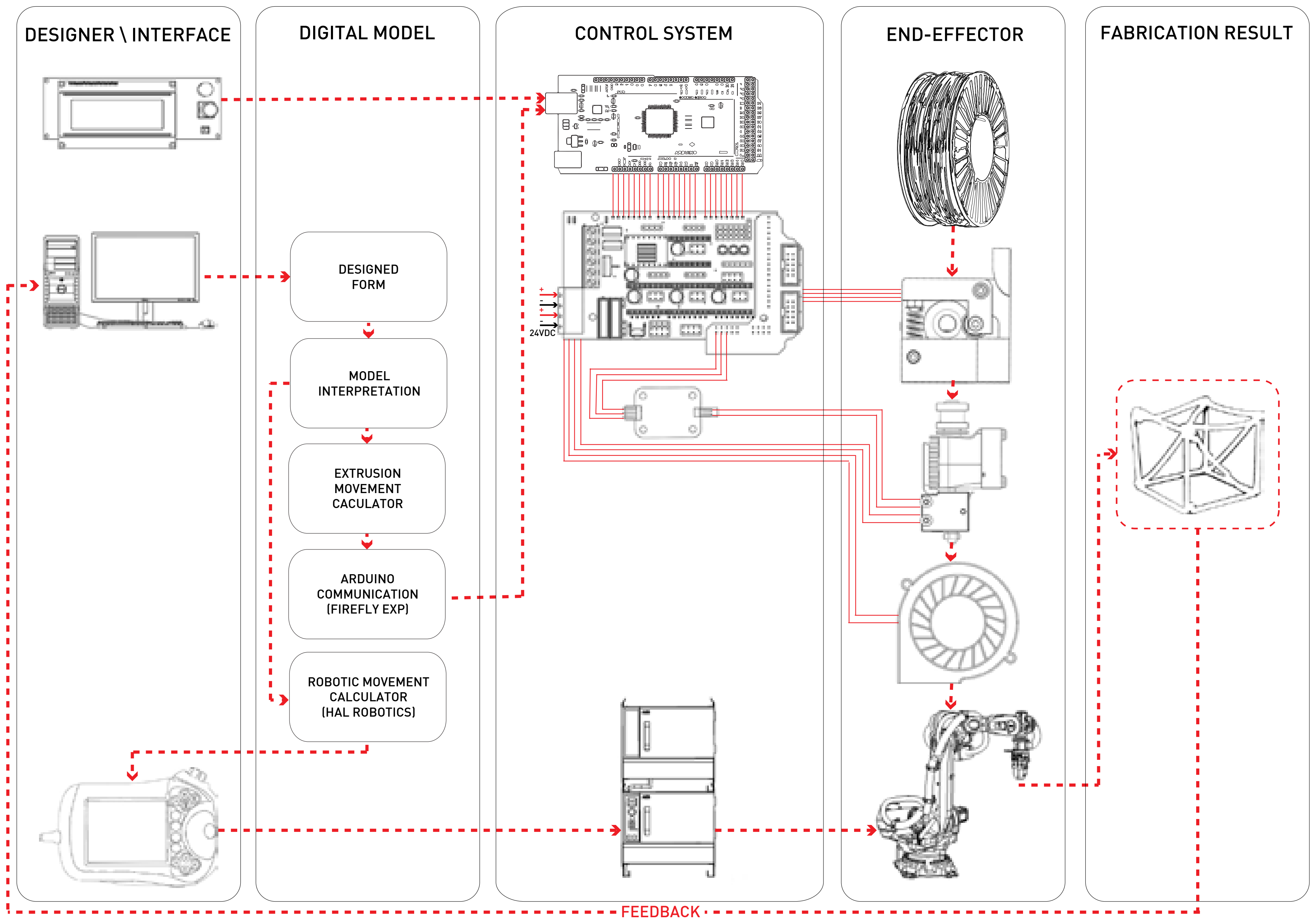
Additive Manufacturing has changed the way we make things. 3D printing technologies such as Fusion Deposition Modelling can quickly translate design ideations into solid forms by precisely depositing layers of material in time with machine movements; the toolpath becomes the form. Spatial printing offers a new way of looking at building 3D forms, harnessing the self-supporting potentials of FDM materials and equipment to create free-standing structures unshackled from the layered constraints of its parent technologies. Here, the designer becomes an informed mediator between material and machine where movement realises form. A complete system was built to harnesses the complexity of robotic movements and respond to the needs of printing materials through experimentation. This thesis illustrates the development of a versatile spatial printing system and subsequent investigations into the craft qualities and freedom of complexity that this system offers to designers and architects.

"Will robotic construction merely emulate manual construction, or become the catalyser for novel building processes? The latter approach invites the designer to consider the ways by which to construct a design process to be as meaningful as the product itself." – Neri Oxman

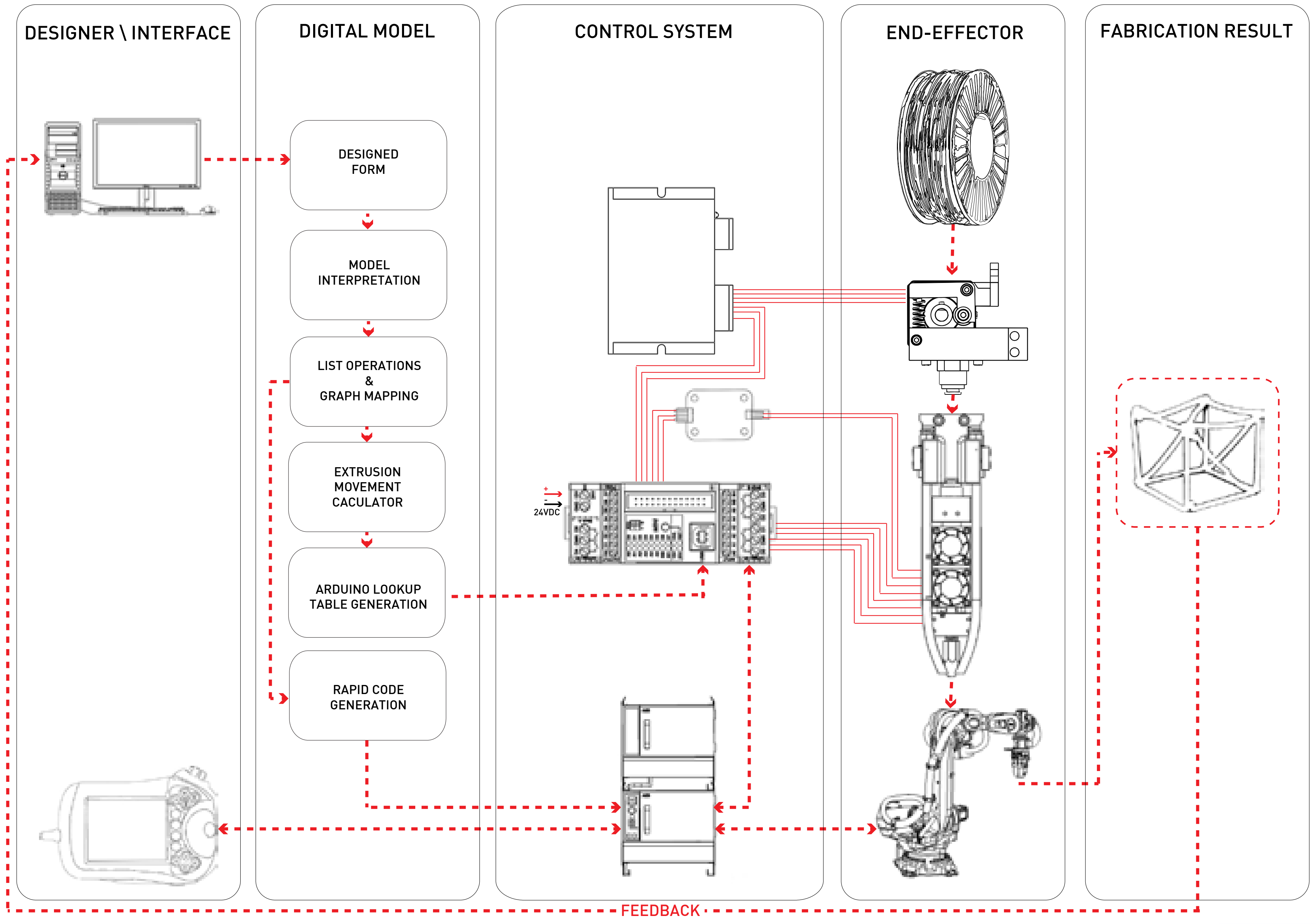


APPENDICES

SPATIAL PRINTING SYSTEM I SCHEMATIC

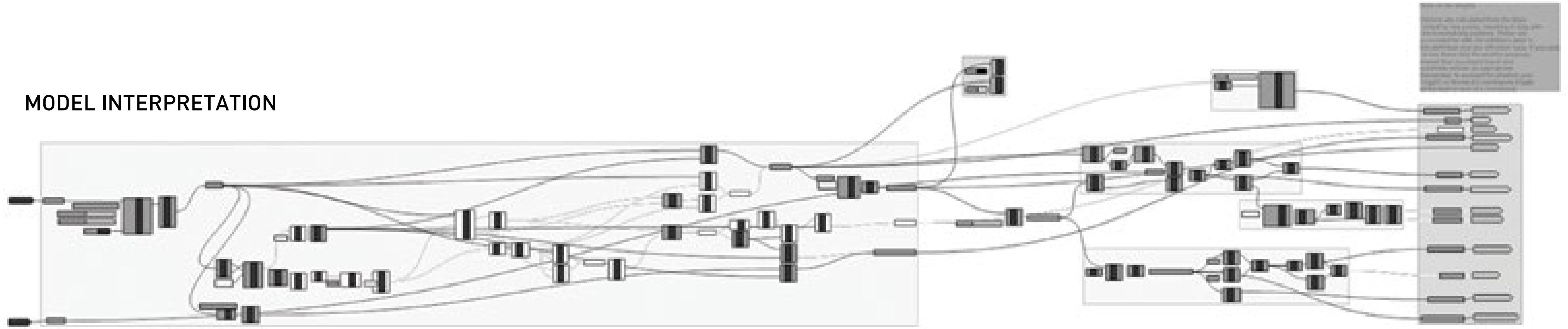


SPATIAL PRINTING SYSTEM II SCHEMATIC

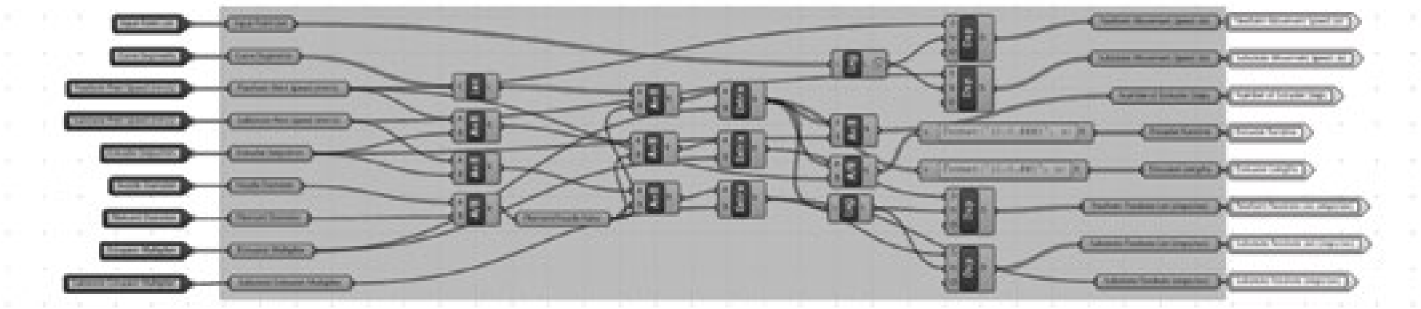


MODEL INTERPRETATION & LIST GENERATION

MODEL INTERPRETATION

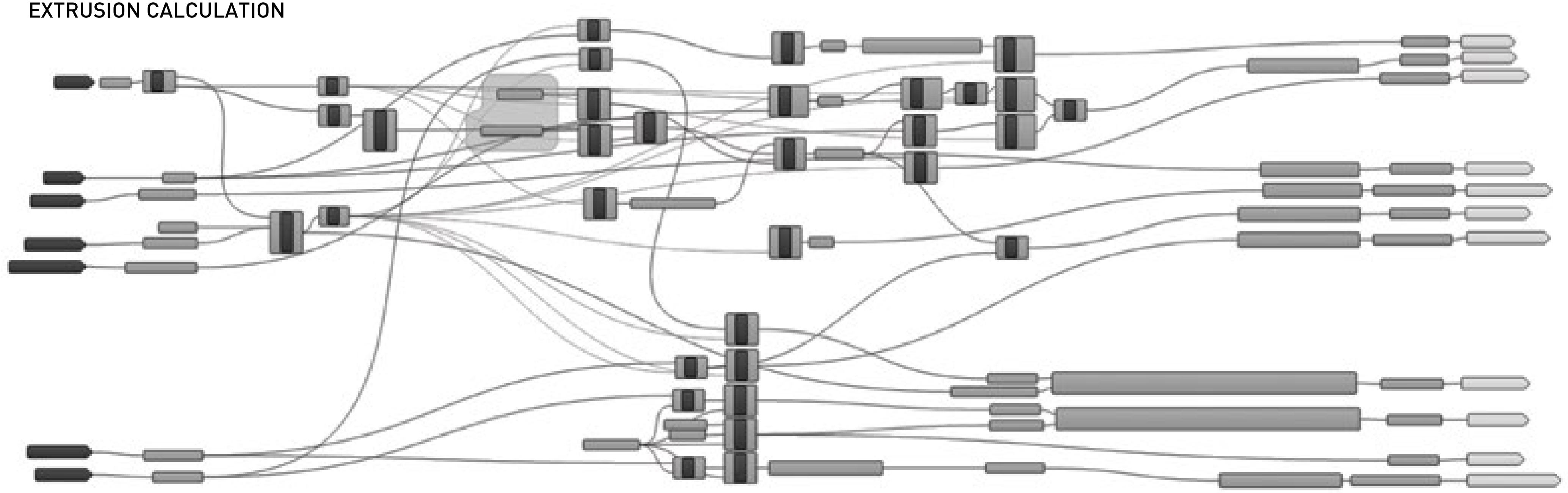


LIST GENERATION

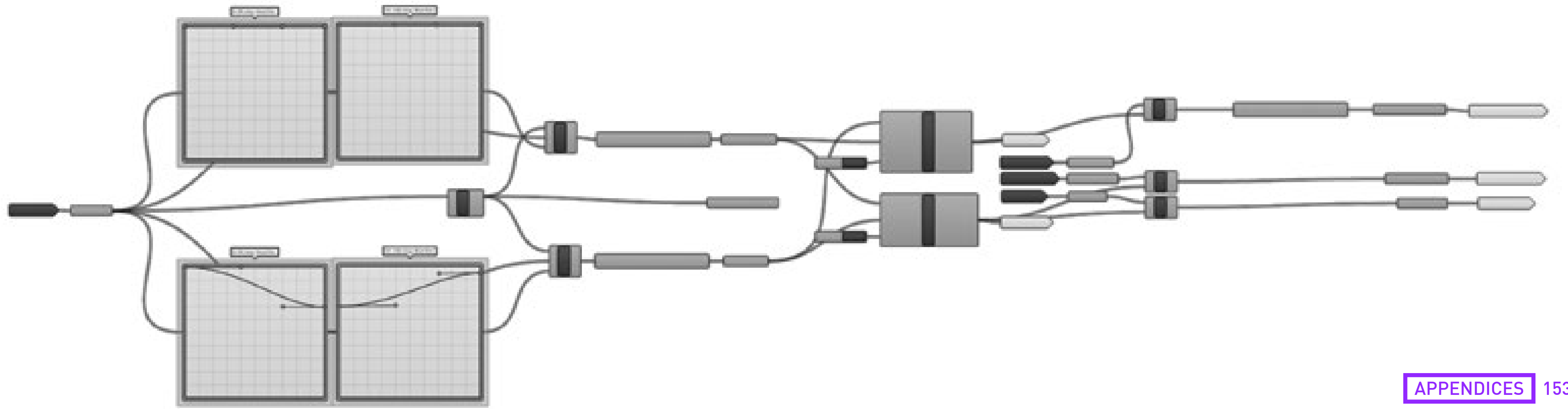


EXTRUSION CALCULATION & GRAPH MAPPER

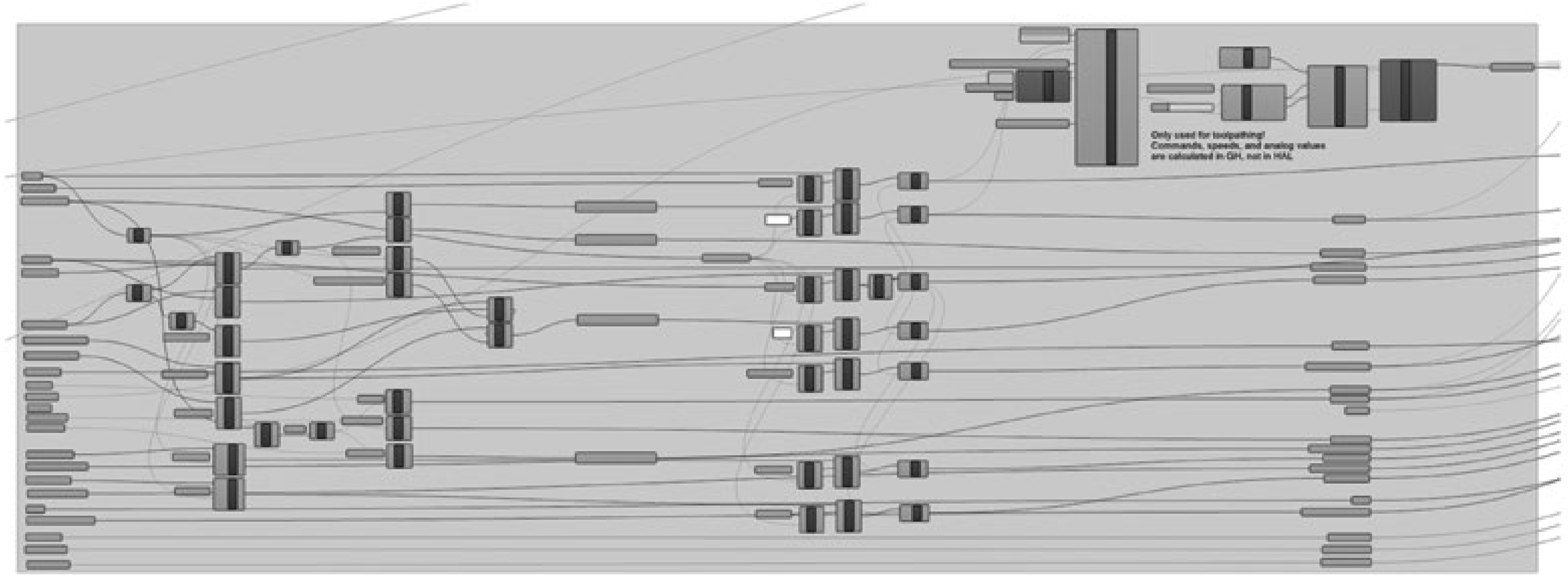
EXTRUSION CALCULATION

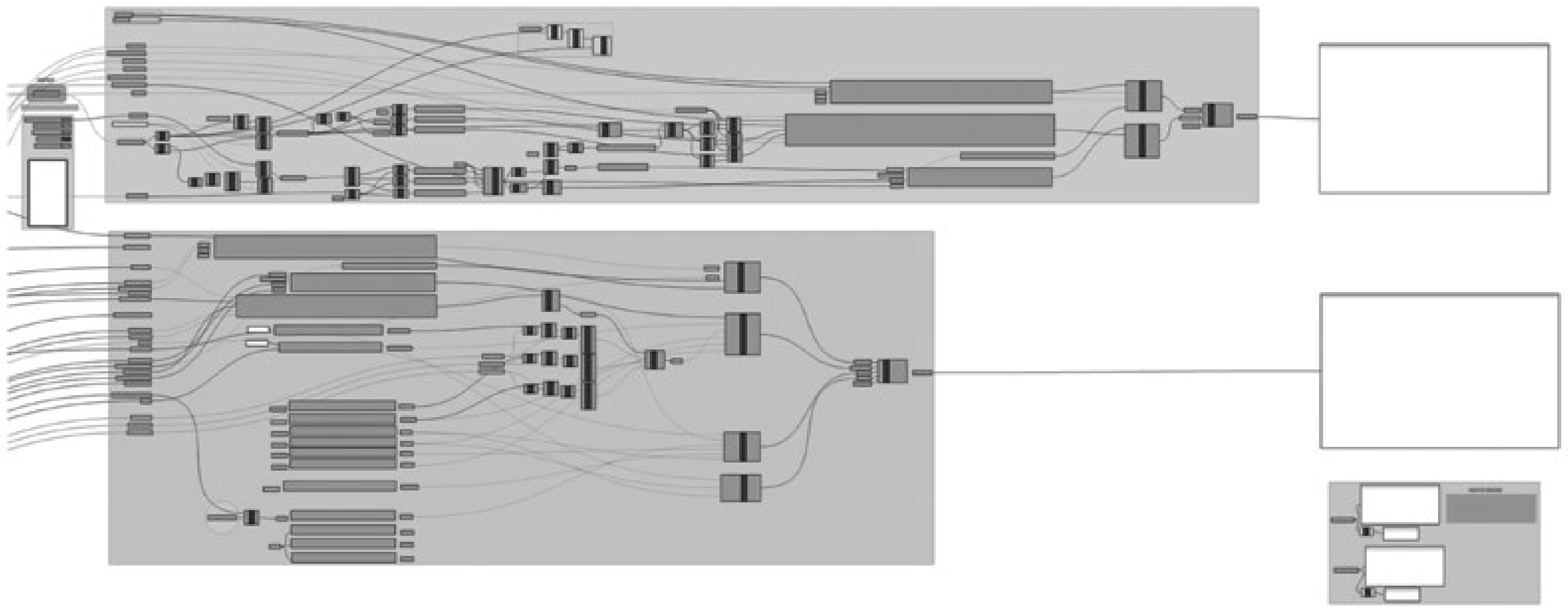


GRAPH MAPPER



LIST OPERATIONS & INVERSE KINEMATICS

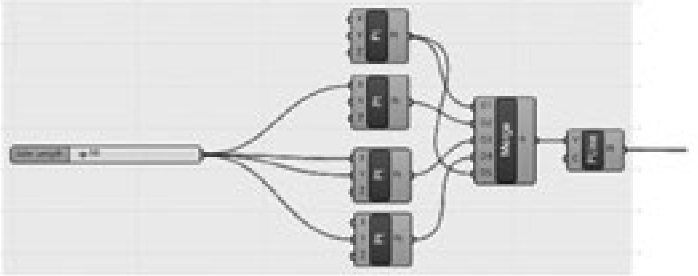




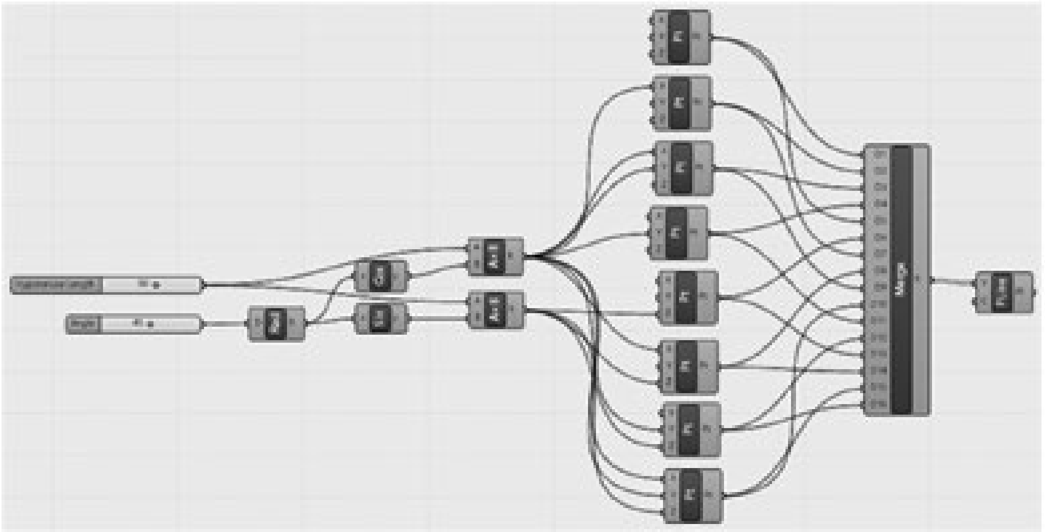
DESIGN MODEL

INPUT DESIGNS - CUBES. SPIROGRAPH, HYPERBOLOID

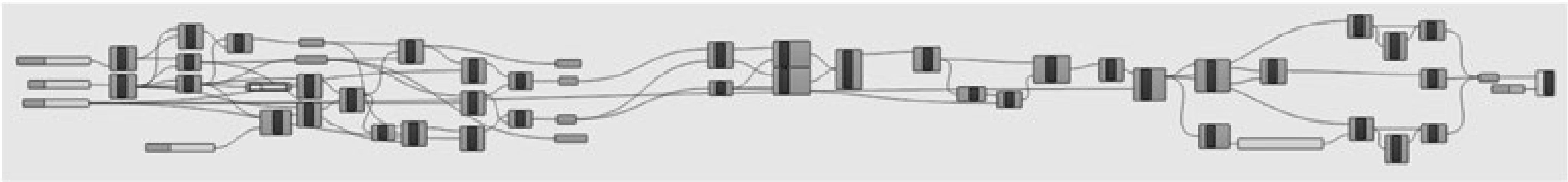
FLAT SQUARE



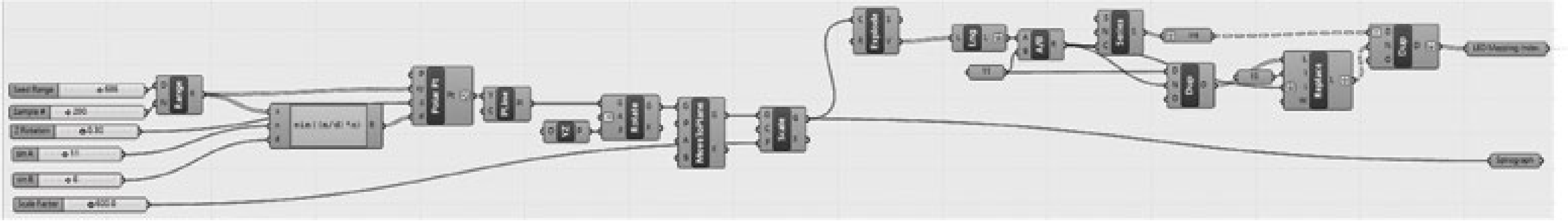
WIREFRAME CUBE



HPERBOLOID

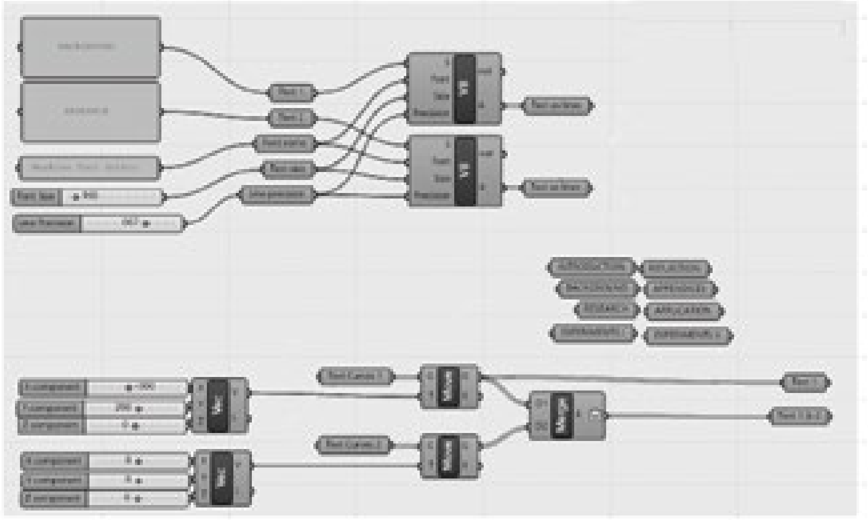


SPIROGRAPH

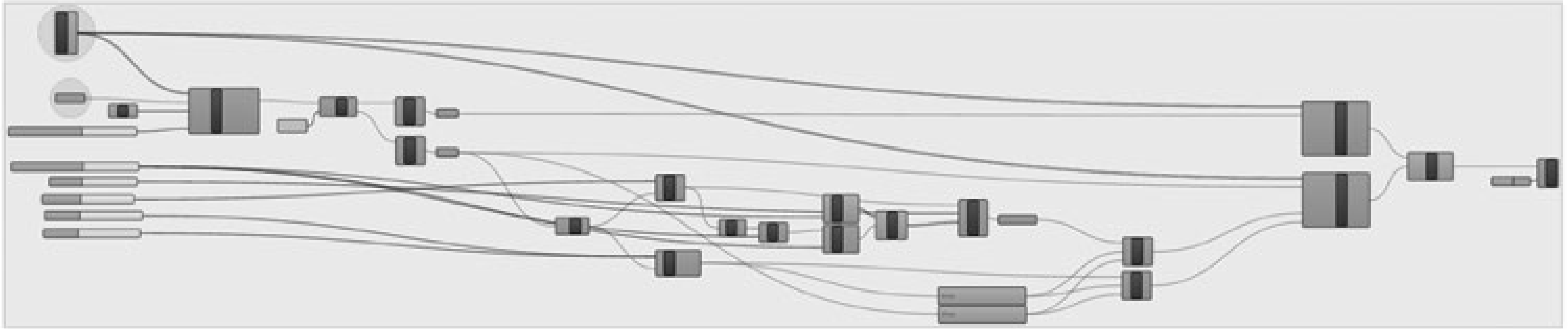


INPUT DESIGNS - TEXT TOOLPATHING & SOLID SLICER

TEXT TOOLPATHING



SOLID SLICER



```
/*
  ABB Robot Arm Extruder

  This program drives the thermoplastic extruder from the VUW ABB Industrial Robot Arm.
*/

#include <Controllino.h>                    // https://controllino.biz/
#include <AccelStepper.h>                   // http://www.airspayce.com/mikem/arduino/AccelStepper/ - Copyright (C) 2010 Mike McCauley
#include <PID_v1.h>                         // http://playground.arduino.cc/Code/PIDLibrary
#include <FastLED.h>                        // http://fastled.io/

// Pins definitions. Pins can be found in the CONTROLLINO-MINI-Pinout.pdf document within the ABB_Extruder folder in your Arduino library folder.

#define TEMP_ANALOG CONTROLLINO_A0            // analog signal from ABB robot to set temperature of extruder
#define STEP_ANALOG CONTROLLINO_A1             // analog signal from ABB robot to set extruder speed
#define TEMP_IO CONTROLLINO_A2                // digital signal from ABB robot to turn temperature on or off
#define STEP_IO CONTROLLINO_A3                // digital signal from ABB robot to turn stepper on or off
// #define VARIABLE CONTROLLINO_A4            // not used
#define TEMP_SENSOR CONTROLLINO_A5            // analog signal from PT100 temperature sensor in extruder

// #define VARIABLE CONTROLLINO_IN0    // Interrupt 0 - Not Used
// #define VARIABLE CONTROLLINO_IN1    // Interrupt 1 - Not Used

#define HEAT_0 CONTROLLINO_D0                 // digital out to control high-level input to heater 0
#define HEAT_1 CONTROLLINO_D1                 // digital out to control high-level input to heater 1
#define ROBOT_TEMPIO CONTROLLINO_D2           // digital output to ABB robot to signal that the extruder is at temperature
#define FAN_0 CONTROLLINO_D3                  // Output for fan 0 (cooling for heatbreak) 2 fans are connected to this output
#define LED_DATA CONTROLLINO_D4               // 5V data output for status LED
#define STEP_STEP CONTROLLINO_D5              // 5V PWM output to stepper motor driver STEP control
#define STEP_DIR CONTROLLINO_D6               // 5V output to stepper motor driver DIR control
#define STEP_ENA CONTROLLINO_D7               // 5V output to stepper motor driver ENA control

// Variable definitions

int tempC;                                  // floating point value for current extruder temperature in degrees C
bool robotEnableTemp = false;               // boolean placeholder for temperature enable reading from robot
bool robotEnableStep = false;               // boolean placeholder for temperature enable reading from robot

double PIDset = 0, PIDin = 0, PIDout = 0;                  // PID variables
// double PIDKp=230, PIDKi=0.5, PIDKd=750;                // PID tuning parameters for relay with tempReadWindow = 1000
double PIDKp = 14.32, PIDKi = 1.22, PIDKd = 41.87;  // PID tuning variables (15.80, 1.4, 44.64 cold, 14.32,1.22, 41.87 warm)
bool tempReady = false;                                   // boolean condition for when extruder is at temperature
int tempReadWindow = 500;                                 // temp loop countdown, also used to control window size of PID time proportioning control
int sigReadWindow = 1000;                      // signal loop countdown, used to define how often signals are read that are not time critical
int fastsigReadWindow = 200;                   // analog read countdown, used to control how often time-critical signals from the robot cabinet are read
int tempTargetOffset = 1;                      // Offset to tune the extruder temp (generally hangs below target)
int tempTargetRange = 10;                      // Temperature window for tempReady
int stepdir = 0;                               // Holds -1, 1 or 0 to turn the motor on/off and control direction
int stepper_speed = 0;                         // Holds current motor speed in steps/second
unsigned long tempSettleTime = 15000;          // Overshoot cooldown time to allow temperature to settle around setpoint (not in seconds)
unsigned long sigWindowstarttime;              // Arduino runtime in milliseconds use to trigger signal reads
unsigned long fastsigWindowstarttime;          // Arduino runtime in milliseconds used to control time-critical signal read timing
unsigned long tempWindowstarttime;             // Arduino runtime in milliseconds used for temperature control timing

// Library Classes

PID HeaterPID(&PIDin, &PIDout, &PIDset, PIDKp, PIDKi, PIDKd, DIRECT);
AccelStepper stepper1(1, STEP_STEP, STEP_DIR);  // Define the stepper and the pins it will use
CRGB LEDs[1];

void setup() {

  pinMode(CONTROLLINO_A0, INPUT);
  pinMode(CONTROLLINO_A1, INPUT);
  pinMode(CONTROLLINO_A2, INPUT_PULLUP);
  pinMode(CONTROLLINO_A3, INPUT_PULLUP);
  // pinMode(CONTROLLINO_A4, INPUT);
  pinMode(CONTROLLINO_A5, INPUT);
  // pinMode(CONTROLLINO_IN0, INPUT);
  // pinMode(CONTROLLINO_IN1, INPUT);
  pinMode(CONTROLLINO_D0, OUTPUT);
  pinMode(CONTROLLINO_D1, OUTPUT);
  pinMode(CONTROLLINO_D2, OUTPUT);
  pinMode(CONTROLLINO_D3, OUTPUT);
  pinMode(CONTROLLINO_D4, OUTPUT);
  pinMode(CONTROLLINO_D5, OUTPUT);
  pinMode(CONTROLLINO_D6, OUTPUT);
  pinMode(CONTROLLINO_D7, OUTPUT);

  // AccelStepper Parameters

  stepper1.setMaxSpeed(10000.0);
  stepper1.setAcceleration(1000);
  stepper1.setMinPulseWidth(2.5);
  stepper1.setEnablePin(STEP_ENA) ;
  stepper1.enableOutputs() ;

  // PID Parameters

  HeaterPID.SetMode(AUTOMATIC);
  HeaterPID.SetOutputLimits(0, tempReadWindow);
  // HeaterPID.SetSampleTime(tempReadWindow); // For relay output

  tempWindowstarttime = millis();
  sigWindowstarttime = millis();
  fastsigWindowstarttime = millis();

  FastLED.addLeds<NEOPIXEL, LED_DATA>(LEDs, 1);

  // Serial.begin(9600);

}

void loop() {
  static unsigned long safety_margin;      // Holds countdown target for tempReady
  static bool safety_trigger = false;      // Safety trigger to ensure only one millis is read
  static byte cooling_threshold = 50;      // Temperature at which heatbreak cooling is enabled
  static byte r_val;                       // Holds current Red value for LED if temp is not ready
  static byte b_val;                       // Holds current Blue value for LED if temp is not ready
  static bool led_blink;                   // Boolean toggle for blinking LED

  // SIGNAL READ LOOP - TIME INSENSITIVE

  if (millis() - sigWindowstarttime > sigReadWindow){

   if (digitalRead(STEP_IO) == true) {     // Checks the robot digital IO signals
    robotEnableStep = true;
   }
   else {
    robotEnableStep = false;
   }

    stepper1.runSpeed();

   if (digitalRead(TEMP_IO) == true) {
    robotEnableTemp = true;
   }
   else {
    robotEnableTemp = false;
   }

    stepper1.runSpeed();

   /* This safety margin ensures that the tempReady signal to both the extruder enable and robot I/O are enabled before extruding.
    safety_trigger and tempReady are enabled once the hotend’s temperature has stabilised within a range around the PIDset value
(tempTargetRange)
    for a period of time (tempSettleTime)
   */

   if (tempC >= (PIDset - tempTargetRange) && tempC <= (PIDset + tempTargetRange) && robotEnableTemp == true) {
    if (safety_trigger == false) {
     safety_margin = millis();
     safety_trigger = true;
    }
    if ((safety_margin + tempSettleTime <  millis())) {
     tempReady = true;
     LEDs[0] = CRGB::Green;
    }
   }
   else {
    tempReady = false;
    safety_trigger = false;
   }

    stepper1.runSpeed();

   if (tempReady == true) {
    digitalWrite(ROBOT_TEMPIO, HIGH);        // Command to enable the temperature ready digital I/O that tells the robot the extruder is ready
    stepper1.runSpeed();

    if (robotEnableStep == true) {
     stepdir = 1;
    }
    else {
    stepdir = 0;
    }
   }
   else {
    digitalWrite(ROBOT_TEMPIO, LOW);
    stepper1.runSpeed();
    stepdir = 0;
   }

   if (tempC > cooling_threshold) {
    digitalWrite(FAN_0, HIGH);
    stepper1.runSpeed();
   }
   else {
    digitalWrite(FAN_0, LOW);
    stepper1.runSpeed();
   }

   if (robotEnableTemp == true) {
    PIDset = readTempAnalogAssign(TEMP_ANALOG);  // Enable if temp is to be read in the main loop

    if (tempReady == false) {
     led_blink = !led_blink;
     if (led_blink == true && tempC < PIDset) {
      r_val = tempC;
      b_val = 255 - tempC;
     }
    else if (led_blink == true && tempC >= PIDset) {
      r_val = 255;
      b_val = 0;
    }
    else {
      r_val = 0;
      b_val = 0;
    }
     stepper1.runSpeed();
     LEDs[0] = CRGB (r_val, 0, b_val);
     }
    }
    else {
     PIDset = 0;
     LEDs[0] =  CRGB::Blue;
    }

   /*
   Serial.print("Setpoint: ");
   Serial.print(PIDset);
   Serial.print(" TempC: ");
   Serial.print(tempC);
   Serial.print(" Output: ");
   Serial.println(PIDout);
   Serial.print ("robotEnableTemp: ");
   Serial.println(robotEnableTemp);
   Serial.print ("robotEnableStep: ");
   Serial.println(robotEnableStep);
   Serial.print ("stepdir: ");
   Serial.println(stepdir);
   Serial.print ("TempReady: ");
   Serial.println(tempReady);
   Serial.print ("Stepper Speed (steps/sec): ");
   Serial.println(stepper_speed);
   //*/

   sigWindowstarttime += sigReadWindow;
  }

  if (millis() - tempWindowstarttime > tempReadWindow){      // TEMPRERATURE READ LOOP
    tempC = readTemp(TEMP_SENSOR);                           // Read temperature using class in signal_values
    stepper1.runSpeed();
    PIDin = tempC;
    tempWindowstarttime += tempReadWindow;                  // Reset the temperature read window
  }

  if (millis() - fastsigWindowstarttime > fastsigReadWindow){      //FAST ANALOG SIGNAL READ LOOP
    stepper_speed = stepdir * readStepAnalogAssign(STEP_ANALOG);  // Find the stepper speed corresponding to the ABB analog value
    stepper1.setSpeed(stepper_speed);                       // Set the stepper speed from the analog reading
    stepper1.runSpeed();                                    // Allow the stepper to move if it needs to at the new speed
    fastsigWindowstarttime += fastsigReadWindow;    // Reset the temperature read window
  }

   if (PIDout > (millis() - tempWindowstarttime)) {
    digitalWrite(HEAT_0, HIGH);                            // This section is used if the heaters are connected to relays
    stepper1.runSpeed();
    digitalWrite(HEAT_1, HIGH);
    stepper1.runSpeed();
   }
   else {
    digitalWrite(HEAT_0, LOW);
    stepper1.runSpeed();
    digitalWrite(HEAT_1, LOW);
    stepper1.runSpeed();
   }

  // Library loops. Must be in the main loop.
  stepper1.runSpeed();
  FastLED.show();
  HeaterPID.Compute();
  stepper1.runSpeed();
  // analogWrite(HEAT_0, PIDout); // Enable if PID does not use relay
  // analogWrite(HEAT_1, PIDout);

}
```

ARDUINO CODE - LOOKUP TABLES

```
const int robotAnalogMax = 337;      // ADC maximum and minimum values from the 10V Analog output (Scaling using 24V supply is 0.03V)
const int robotAnalogMin = 0;
const int OVERSAMPLING = 16;

const int PT100LUTLength = 49;

const unsigned int PT100table[PT100LUTLength][2] PROGMEM = {
{  0 * OVERSAMPLING  , 0 } ,
{ 227 * OVERSAMPLING  , 1 } ,
{ 235 * OVERSAMPLING  , 10  } ,
{ 246 * OVERSAMPLING  , 20  } ,
{ 254 * OVERSAMPLING  , 30  } ,
{ 262 * OVERSAMPLING  , 40  } ,
{ 270 * OVERSAMPLING  , 50  } ,
{ 278 * OVERSAMPLING  , 60  } ,
{ 286 * OVERSAMPLING  , 70  } ,
{ 295 * OVERSAMPLING  , 80  } ,
{ 303 * OVERSAMPLING  , 90  } ,
{ 311 * OVERSAMPLING  , 100 } ,
{ 319 * OVERSAMPLING  , 110 } ,
{ 329 * OVERSAMPLING  , 120 } ,
{ 338 * OVERSAMPLING  , 130 } ,
{ 344 * OVERSAMPLING  , 140 } ,
{ 352 * OVERSAMPLING  , 150 } ,
{ 360 * OVERSAMPLING  , 160 } ,
{ 368 * OVERSAMPLING  , 170 } ,
{ 376 * OVERSAMPLING  , 180 } ,
{ 385 * OVERSAMPLING  , 190 } ,
{ 393 * OVERSAMPLING  , 200 } ,
{ 401 * OVERSAMPLING  , 210 } ,
{ 409 * OVERSAMPLING  , 220 } ,
{ 417 * OVERSAMPLING  , 230 } ,
{ 424 * OVERSAMPLING  , 240 } ,
{ 432 * OVERSAMPLING  , 250 } ,
{ 440 * OVERSAMPLING  , 260 } ,
{ 446 * OVERSAMPLING  , 270 } ,
{ 454 * OVERSAMPLING  , 280 } ,
{ 462 * OVERSAMPLING  , 290 } ,
{ 469 * OVERSAMPLING  , 300 } ,
{ 477 * OVERSAMPLING  , 310 } ,
{ 485 * OVERSAMPLING  , 320 } ,
{ 493 * OVERSAMPLING  , 330 } ,
{ 499 * OVERSAMPLING  , 340 } ,
{ 507 * OVERSAMPLING  , 350 } ,
{ 514 * OVERSAMPLING  , 360 } ,
{ 522 * OVERSAMPLING  , 370 } ,
{ 528 * OVERSAMPLING  , 380 } ,
{ 536 * OVERSAMPLING  , 390 } ,
{ 544 * OVERSAMPLING  , 400 } ,
{ 614 * OVERSAMPLING  , 500 } ,
{ 681 * OVERSAMPLING  , 600 } ,
{ 743 * OVERSAMPLING  , 700 } ,
{ 804 * OVERSAMPLING  , 800 } ,
{ 861 * OVERSAMPLING  , 900 } ,
{ 917 * OVERSAMPLING  , 1000  } ,
{ 968 * OVERSAMPLING  , 1100  }
};

const int TempLUTLength = 8;  // LookUp Table list length
const int vMargin1 = 5;       // The target is found when the lookup value is higher than the ADC value, this margin ensures the correct target is found

const unsigned int RobotAnalogTempTable[TempLUTLength][2] PROGMEM = {
{ ( 0  + vMargin1) * OVERSAMPLING  , 180  } ,
{ ( 42  + vMargin1) * OVERSAMPLING  , 185  } ,
{ ( 84  + vMargin1) * OVERSAMPLING  , 190  } ,
{ ( 126  + vMargin1) * OVERSAMPLING  , 195  } ,
{ ( 168  + vMargin1) * OVERSAMPLING  , 200  } ,
{ ( 211  + vMargin1) * OVERSAMPLING  , 205  } ,
{ ( 253  + vMargin1) * OVERSAMPLING  , 210  } ,
{ ( 295  + vMargin1) * OVERSAMPLING  , 215  }
 };

const int StepLUTLength = 10;  // LookUp Table list length
const int vMargin2 = 5;       // The target is found when the lookup value is higher than the ADC value, this margin ensures the correct target is found

const int RobotAnalogStepTable[StepLUTLength][2] PROGMEM = {
{ robotAnalogMin * OVERSAMPLING  , 0 } ,
{ (90 + vMargin2) * OVERSAMPLING  , 100 } ,
{ (120 + vMargin2) * OVERSAMPLING  , 200 } ,
{ (150 + vMargin2) * OVERSAMPLING  , 300 } ,
{ (180 + vMargin2) * OVERSAMPLING  , 400 } ,
{ (210 + vMargin2) * OVERSAMPLING  , 500 } ,
{ (240 + vMargin2) * OVERSAMPLING  , 600 } ,
{ (270 + vMargin2) * OVERSAMPLING  , 700 } ,
{ (300 + vMargin2) * OVERSAMPLING  , 800 } ,
{ (320 + vMargin2) * OVERSAMPLING  , 900 }
};

int readTemp (int _TEMP_SENSOR)  {

  /*
   *  This function reads the voltage of a thermistor and converts it to a corresponding temperature in deg C
   *
   *  This sketch empolys a lookup table to convert voltage to temperature, which is stored in the EEPROM to save on processing
   *  The lookup table  converts ADC values calculated from experimental and converted using forumulas in excel into degrees C
   *  This spreadsheet can be found in the ABB Extruder systems folder
   *
   */

  int _tempC; // Return value for temperature reading
  int ADC_value;  // Raw ADC value reading
  int ADC_Low;   // The Lower ADC matching value
  int ADC_High;   // The Higher ADC matching value
  int Temp_Low;  // The Lower whole-number matching temperature
  int Temp_High;  // The Higher whole-number matching temperature
  bool power_supply; // Boolean for whether the 5V supply is from USB or 5V regulator to account for voltage drop
  int temp_offset = 0; // Temperature offset to account for voltage drop if using 5V over USB

  ADC_value = (analogRead(_TEMP_SENSOR) * OVERSAMPLING);

  for (int i=0; i <= (PT100LUTLength - 1); i++){    // Step through the lookup table and look for a match
    if (pgm_read_word( &PT100table[i][0] ) > ADC_value) {  // Find the closest Higher ADC value
      ADC_High = pgm_read_word( &PT100table[i][0] );
      Temp_High = pgm_read_word( &PT100table[i][1] );      // Record the closest Higher whole-number temperature

      // Get the closest Lower whole-number temperature, taking the lower table boundary into account
      if (i != 0)  {
        ADC_Low = pgm_read_word( &PT100table[i-1][0] );
        Temp_Low = pgm_read_word( &PT100table[i-1][1] );
      }
      else  {
        ADC_Low = pgm_read_word( &PT100table[i][0] );
        Temp_Low = pgm_read_word( &PT100table[i][1] );
      }
      _tempC = int(( map(ADC_value, ADC_Low, ADC_High, Temp_Low*100, Temp_High*100) )/100)+ temp_offset;
      break;  // exit for-next loop after the match is detected
    }
  }
   return (_tempC);
}

int readTempAnalogAssign (int _TEMP_ANALOG)  {

    /*
  *  This function reads the analog voltage from the ABB cabinet and maps it to a corresponding value in degrees C.
  *  These temperatures can be defined arbitrarilly or as an output list of temperature values from Grasshopper
  *  (ie for prints using multiple temperatures on the fly)
  *
  *  Voltages are set here manually as divisions of the maximum analog voltage by the total list length
  *  Temperatures are mapped depending on high and low values set below
  *
  */

  int _tempAnalogC;   // Return value for temperature reading
  int ADC_val1;          // Raw ADC value reading

  ADC_val1 = (analogRead(_TEMP_ANALOG) * OVERSAMPLING);

  for (int i=0; i <= (TempLUTLength - 1); i++){    // Step through the lookup table and look for a match
    if (pgm_read_word( &RobotAnalogTempTable[0][0] ) == ADC_val1) {         // If condition in case ADC is 0
      _tempAnalogC = pgm_read_word( &RobotAnalogTempTable[0][1] );         // Record the corresponding temperature value
      break;                                                // Exit for-next loop after the match is detected
    }
    else if (pgm_read_word( &RobotAnalogTempTable[i][0] ) > ADC_val1) {     // Find the closest Higher ADC value
      _tempAnalogC = pgm_read_word( &RobotAnalogTempTable[i][1] );         // Record the corresponding temperature value
      break;
      }
      else {
      _tempAnalogC = pgm_read_word( &RobotAnalogTempTable[0][1] );         // If no condition is met, temp reverts to min value (usually 0)
      }
            }
    return (_tempAnalogC);
}

int readStepAnalogAssign (int _STEP_ANALOG)  {

      /*
  *  This function reads the analog voltage from the ABB cabinet and maps it to a corresponding value in steps/sec
  *  These stepper values can be defined arbitrarilly or as an output list of extrusion rate values from Grasshopper
  *  This list should parallel the list of robot speeds (s1, s2, s3, stravel etc) with their corresponding extrusion rates from experimentation
  *
  *  Stepper  motor working equation:
  *  200steps/rev motor * 5 (5.18) gearing ratio * 8 x microstepping = 8000 (8288) steps/rev stepper motor output
  *
  *  From documentation, pinch gear has a ratio of 460steps/mm using the same stepper motor.
  *  This number is divided by 2 because we are using 8 x microstepping instead of 16 x microstepping -> 230steps/mm
  *
  *
  *  Voltages are set here manually as divisions of the maximum analog voltage by the total list length
  */

  int _stepAnalog;     // Return value for stepper rate
  int ADC_val2;           // Raw ADC value reading

  ADC_val2 = (analogRead(_STEP_ANALOG) * OVERSAMPLING);

  for (int i=0; i <= (StepLUTLength - 1); i++){    // Step through the lookup table and look for a match
    if (pgm_read_word( &RobotAnalogStepTable[0][0] ) == ADC_val2) {               // If condition in case ADC is 0
      _stepAnalog = pgm_read_word( &RobotAnalogStepTable[0][1] );                 // Record the corresponding temperature value
      break;                                                                      // Exit for-next loop after the match is detected
    }
    else if (pgm_read_word( &RobotAnalogStepTable[i][0] ) > ADC_val2) {     // Find the closest Higher ADC value
      _stepAnalog = pgm_read_word( &RobotAnalogStepTable[i][1] );             zz// Record the corresponding temperature value
      break;
      }
      else {
      _stepAnalog = pgm_read_word( &RobotAnalogStepTable[0][1] );        // If no condition is met, temp reverts to min value (usually 0)
      }
            }
    return (_stepAnalog);
}
```

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