Multi-Resolution in Architectural Design and Robotic Fabrication:
Novel resolution based computational method and Free Oriented Additive Manufacturing technique

by

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In collaboration with

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Submitted to the School of Architecture
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Abstract

Digital technology has already started to use excess data and computation to design and fabricate reality as it appears. The resolution of detail is closer to nature than ever, with all of its apparent randomness and irregularity. The standardization of the Industrial Revolution is obsolete—additive technology now allows us to individually design, calculate, and fabricate each voxel.

According to Mario Carpo, as each digital voxel is individually 3D printed, there is no need to make any voxel-generated volume identical to any other. Just as 20 years ago we learned that we could laser print one thousand different pages, or one thousand identical copies at the same unit cost, today we can 3D print any given volume of a given material at the same volumetric cost, based on its resolution, not on geometry or configuration.

The computational part of this research develops the concept of *Arxel*©, and its implementation in construction technology, within its context in a proposed Multi-Resolution Methodology of design. *Arxel* is a digital architecture unit that may provide insight in the construction of digital architectures through the lens of genotype and phenotype but particularly through the lens of economy, fundamental in providing sustainable alternatives.

3D Printed cellular and lattice-like structures are potential to large-scale robotic construction because of their light weight multifunctional application. In order to break the constraint of horizontal stacking principal, the effect of orienting the extrusion direction on non-layer spatial fused deposition modeling is studied.

The fabrication part of this research presents a novel Additive Manufacturing application of Fused Deposition Modeling on varying spatial conditions, varying deposition direction and varying geometry to adapt to complex infrastructure conditions.

Free Oriented Additive Manufacturing provides a fabrication technique for architectural speculation of previously unexploited spaces, providing the means for reconfiguring and bonding new qualities to existing infrastructures. It has the potential to produce complexity of form, bespoke performance and mass instantiations.

This proposed technique is tested under four case studies, each one using a different combinatory of resolution-based computational design methods and fabrication workflow setups of the same robotic cell.

These case studies demonstrate the conception of detaching 3D printing processes to horizontal work beds, explain its fabrication process, test over existing porous surfaces, and conclude by evaluating the robotic implementation in additive manufacturing applications by means of reachability, flexibility and benefits of compactness of the end of the arm tool (EOAT)

Acknowledgements

As a way to understand the impact in design and architecture of digital processes such as a unit of fabrication that is entirely thought and designed through computational means, we may need to explore new sensibilities through different lenses. Without innate dedication and sensibilities for design of architecture, novel workflows and methods for design thinking might not have a relevant impact in the field. I would first like to thank my thesis advisor and mentor, Jeremy Ficca, who taught me how to think about new emerging sensibilities and their relation in already existing ones, and to always orient this research towards the scale of architecture; who believed in this collaborative research and provided me with the necessary tools to make it possible; who encouraged me to take a clear position when defining the research. Thank you, Jeremy, for always dedicating your time and effort in my work and my life since the beginning during this journey, for giving me the opportunity to teach in your Studio, and for your insightful advice.

My work would have been much less developed without the input of Josh Bard, Mary-Lou Arscott, and Daniel Cardoso. I am always grateful to the imprint they have left forever in my professional and academic perspective. Josh, thanks for all your insightful advice in how to approach this research in successful ways. Thanks for being the figure who has conducted the robotic fabrication towards what it is now, for inputting different perspectives and complementary approaches, and thank you for being the hinge between the computation and the fabrication processes. Mary-Lou, your words full of wisdom and insight shaped this research from the very beginning. Our discussions about the understanding of digital in architecture framed the research in meaningful manners. The references you gave and the clarity of your feedback was critical in the development of this research. Daniel: the computational part of this research and its underlying fundamental concepts of algorithmic thinking is in great part your contribution. Numerous explorations about computational strategies are the result of your vision. Thank you again for the time you have dedicated into this work.

This thesis would not have been possible without the contribution of Kai Gustchow. Through your Thesis Prep course and discussions about how this thesis might be framed, you taught me how to write a statement for a research, the difference between design research and research through design, and how to make an insightful statement when communicating a project. A special thank you to Terry Hrizt, for all those moments shared in dFab and your flexibility and ability to provide with all necessary advice regarding the use of any of the resources in dFab. I would also like to thank the administration of the school of architecture, especially Dave Koltas, for all the support received, for your care and for make possible this fantastic collaboration.

I owe much gratitude to Prof. Steve Lee, Head of the School of Architecture. Thank you for your words, for putting me in connection with interesting people, and for allowing me to come and join such an institution as Carnegie Mellon. I would also like to thanks Daragh Byrne, Stefan Grubber, Dana Cupkova, Garth Zeglin, Brian Peters and Robert Zacharias. Each of you also contributed to this research through insightful conversations and advice. Thanks to Jesus Anaya (DCTA PhD. Thesis Director) and to Francisco Hernandez Olivares (DCTA PhD. Program Coordinator).

This project has been funded by CMU GuSH Research Grant, the Frank Ratchye Studio for Creative Inquiry and CONACYT – National Science and Technology Council of Mexico. Thank all of you for your immense support and to have provided with the necessary infrastructure to make the research happening. Thanks also to the George W. Anderson, Jr. Award, as the work showcased is part of the research and the prize is invested in it.

I came to Carnegie Mellon to join the MAAD program – Masters of Advanced Architectural Design. Prior to that, I had the opportunity to do a Research Assistantship under the umbrella of Jeremy Ficca and Terry Hritz. Since then, I never stopped working at the school, becoming Teaching Assistant in different courses and working as Studio Instructor at Pre-College Architecture during the summer of 2017 under the coordination of Spike Wolf, as a Research Assistant under the umbrella of Josh Bard and Dana Cupkova, and working as 2nd Year Studio Instructor under the coordination of Jeremy Ficca. It would not be fair not to mention all of this, as it shaped my person and my profession at this fantastic Institution. As a direct consequence, my research has indirectly been shaped and looked through new insight that this experience has given.

As I mentioned before, this research is product of a successful collaboration. Luis Borunda, thank you for agreeing coming to Carnegie Mellon to do a collaborative research. Together, we keep learning and teaching each other. Your talent and unique vision of architecture, your skills and perception have been crucial in the development of the research. We have spent uncountable hours working at home or at dFab. We have had numerous conversations about the research in particular and life and architecture in general. We met in Barcelona a few years back and here we are together again. You are one of the few people in which one feels completely comfortable working with, under pressure and different circumstances. Thanks for all your support and feedback given to this. This research is yours too.

Last but not least, I would like to thank my family for all the support given. The decision of joining Carnegie Mellon was slow cooked between all of us. Your support, both psychological and economic, has always been crucial. Thanks for always giving such advice that was always right and helped me take the right directions. Your patience and care has always given me that necessary push to look forward and forgot about minor things. Thanks for always being there.

Contents

CHAPTER 1

Introduction

Digital resolutions, big data and Additive Manufacturing

1.1 Introduction to digital methodologies

Since the existence of CAD software, designers have been constantly learning new drawing skills through computational means. Accordingly, the knowledge of the tool has been a steady feature for architects in order to draw, develop and communicate their projects. Architects, for the last thirty years, have been adapting their skills to new software in order to be prepared for market exigencies. In this computational era for designers, the tool presents a direct imprint in the shape of their buildings (Carpo, 2017).

According to Mario Carpo, during the second turn in architecture, architects might start using computation in a raw format (i.e. coding directly a script rather than using already built-in plugins or software) as ways to explore novel design methodologies. This does not only have consequences in the shape of the design, but also and more importantly, raises new ways to think architecture, therefore, more likely than not, new sensibilities are about to have an impact in architecture.

During the following years, we might face a coexistence of already stablished sensibilities with new emerging insights coming from these new methodologies.

This is possible due to the fact that architects and designers are closer than ever to computational and fabrication technologies. Same as ten years ago we were exploring parametric software (i.e. Grasshopper plugin for Rhinoceros, McNeel or Dynamo, Autodesk), now we are starting to use our own code (Python GH) as a higher degree of freedom in design is given, rather than the mentioned examples. We can see how Gramazio Kohler use this workflow in their recent work (Gramazio and Kohler, 2017).

This is in great part, because parametric software started to introduce a new design thinking approach to architects: algorithm thinking, or procedural design based thinking. As we started to understand how this visual scripting software works, we are able to better understand the process of design by coding algorithms.

1.2 Computational Resolution

The beginning of computational geometry as an independent intellectual discipline is usually dated around 1975, when Michael Shamos and Dan Hoey proposed algorithmic solutions for a host of basic geometric tasks (Shamos 1975, Shamos and Hoey 1975,1976). They defined computational geometry as the study of the computational complexity of geometric problems. It is important to notice the implicit but significant shift from a continuous to a discrete conception of geometry. Application areas use geometry to model a presumably continuous reality, while computation complexity relates the finite amount of time it takes to solve a problem with the finite size with the problem presents itself. Within a few years after its inception, computational geometry developed a strong affinity to discrete geometry as practised by combinatorialists (Erdos 1979, Pach and Agarwal 1995). This affinity was natural and helped the field to mature to a point where it is ready for a reorientation back to its continuous roots.

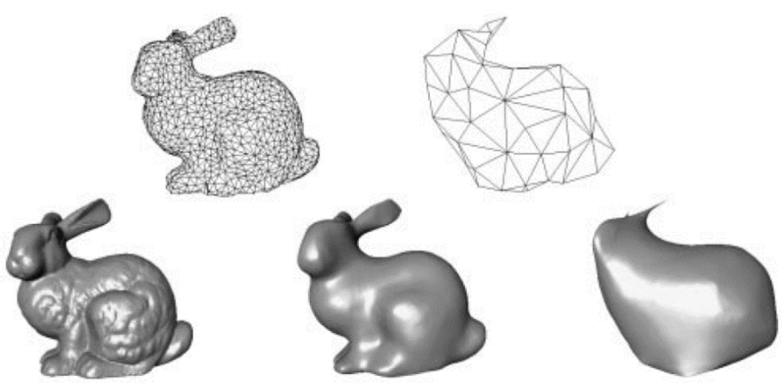


Figure 1. Stanford Bunny at different resolutions

In the last years triangle meshes have become increasingly popular and are nowadays intensively used in many different areas of computer graphics and geometry processing. In classical Computer Aided Geometric Design (CAGD), irregular triangle meshes developed into a valuable alternative to traditional spline surfaces, since their conceptual simplicity allows for more flexible and highly efficient processing.

Moreover, the consequent use of triangle meshes as surface representation avoids error-prone conversions, e.g., from CAD surfaces to mesh-based input data of numerical simulations. Besides classical geometric modelling, other major areas frequently employing triangle meshes are computer games and movie production. In this context geometric models are often acquired by 3D scanning techniques and have to undergo post-processing and shape optimization techniques before being actually used in production.

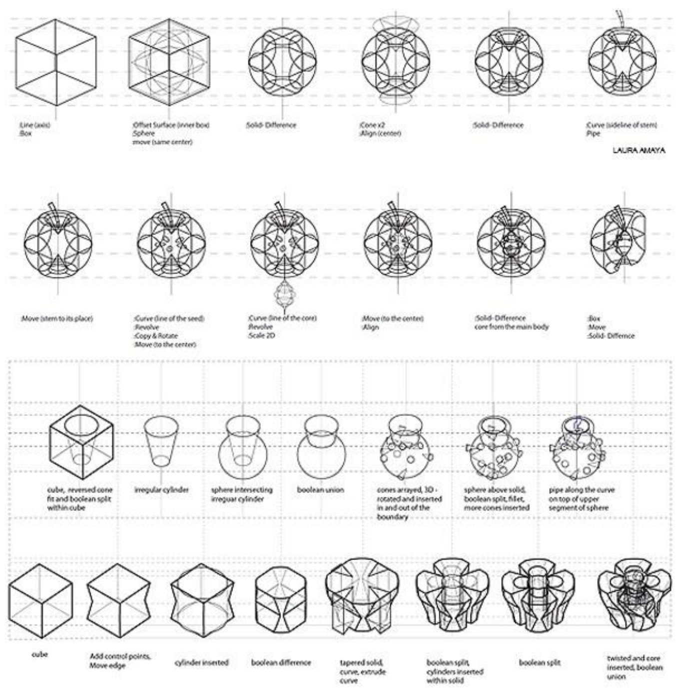


Figure 2. Intro to Computational Geometry, EPIPHYTE-Lab

1.3 Compression algorithms

Until a few years ago, we always needed more data than we had. Today, for the first time, we seem to have more data than we need. According to Mario Carpo, logarithms are one of the most effective data-compression technologies of all time. By translating big numbers into small numbers and therefore, their possible consequent mathematical operations, they made difficult arithmetical calculations much faster and less error-prone. However, they are only practical when paired with logarithmic tables, and logarithmic tables would be useless unless printed (if they had to be copied by hand, the result would be too labour-intensive to be affordable and too error-prone to be reliable). Logarithms are, therefore, the quintessential mathematics of the age of printing; a data-compression technology of the mechanical age. Today, computers have de-invented logarithms; they are just a technology of data compression that digital computers simply do not need any more (Carpo 2017).

1.4 Excess of data

By the mid-sixteenth century, with book production surging due to print, librarians and book dealers might have been facing the first big data crisis in history, as many of their traditional tools and practices were being overwhelmed by technological change. To help keep track of this unprecedented wave of authors and titles, a universal method of classification needed to be devised, based on index keys (Carpo 2017). Similarly, in architecture now, we are required to manage this amount of data by the use of algorithms that sort, cull and curate the excess of information.

1.5 What is digital

Neil Leach argues that 'while there is clearly a practice of designing that involves the use of digital tools, there is no product as such that might be described as digital' (Leach, 2015). Digital design and fabrication tools might have a specific type of design, but they could also be used for objects which are not 'digital' (Jimenez Garcia, Retsin, 2015). However, Mario Carpo provides a counter-argument to Neil Leach's statement. Carpo identifies the digital character of a design method, arguing for the intrinsically discrete nature of computational processes (Carpo, 2014). Another approach is given by MIT professor Neil Gerschenfeld, who distinguishes between analog and digital organizations (Gerschenfeld, Carney et al, 2015). He draws a parallel to the way how data is organized. Analog means continuous, digital data, on the other hand, is discrete. In an analog system, a piece of matter has infinite connection possibilities, whereas a discrete or digital system only has a limited number (Ward, 2010).

1.6 New role of architects

The diagram shows at a very basic level, the role of the architect until the 21st century. An architect generally plays a centralized role in the process as a, quote and quote, guru, who by analog ways tries to design in respond to a problem, and the fabrication happens at the end of the stream. The architect manages the site but does not have the ownership of the fabrication. Now, the architect's role is decentralized, which designs through algorithms capable of produce editable instantiations by the user. The architect then curates this design and fabricate it. The end product is a reusable and hackable architecture (Figure 3).

All these questions about the architect's role and about what architecture is nowadays has been out for a while, and recently more due to the urgent necessities at a worldwide level to fight against poverty, scarcity and unsustainability, as it is stated by the United Nations Global Agenda. By 2030, everyone will live in adequate, safe and affordable housing, they stated.

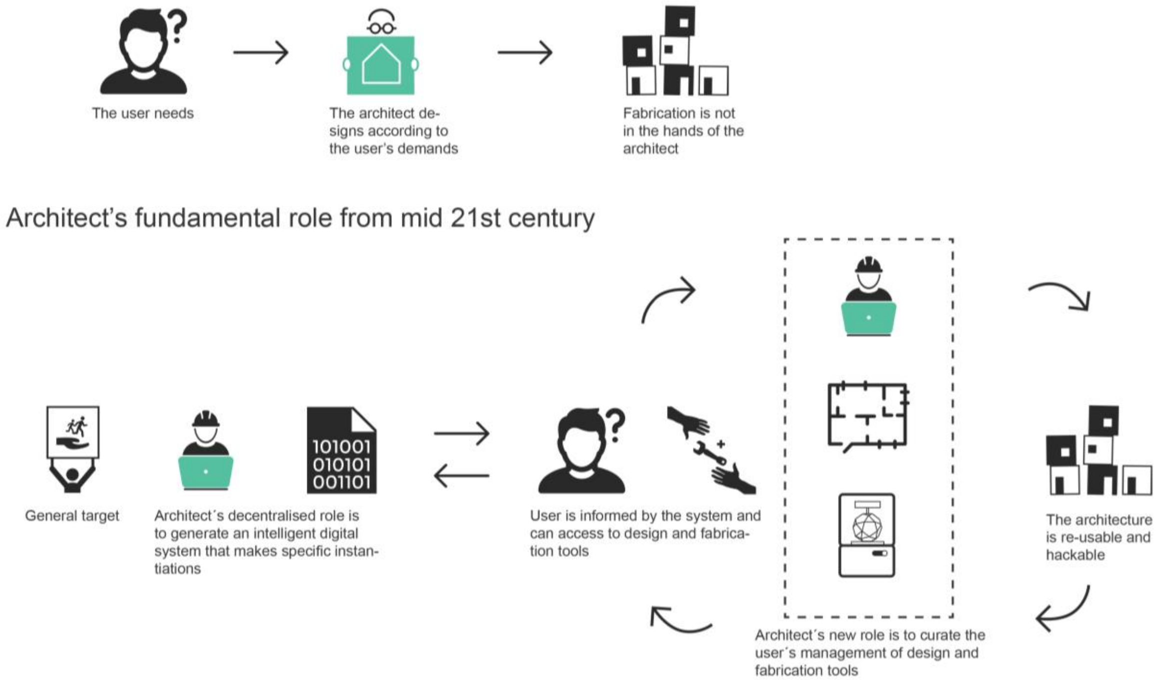


Figure 3. Change of the role of the architect

1.7 Additive Manufacturing Background

Additive Manufacturing (AM) is a revolutionary technology due to its versatility and flexibility to produce custom engineered designs. Fused Deposition Modelling (FDM) is an AM process that extrude molten thermoplastic filament through a heated nozzle layer by layer in a horizontal prescribed manner. A major limitation of applying FDM technologies to construction automation is the time it takes to produce large-scale builds.

Current advances in robotically augmented AM have recently proved to significantly reduce cost and time of construction of complex shapes (de Soto et al. 2018). Spatial FDM is a method by which molten polymer sections are configured in a space frame pattern that has demonstrated capability of fabricating functional products with optimized performance (Liu, Li, and Li 2018) and reduce fabrication time of prototype prints by differentiating the local value of a printed specimen along extrusion process (Mueller et al. 2014).

Advances in automation deconstruction and re-customization provide tools for reconsidering existing infrastructures retro-fitting (Bock 2015). Novel computational design methods (Retsin and Jimenez Garcia 2016) and fabrication techniques impulse the emerging body of research of Spatial FDM in an architecture scale (Hack et al. 2014; Soler, Retsin, and Jimenez Garcia 2017).

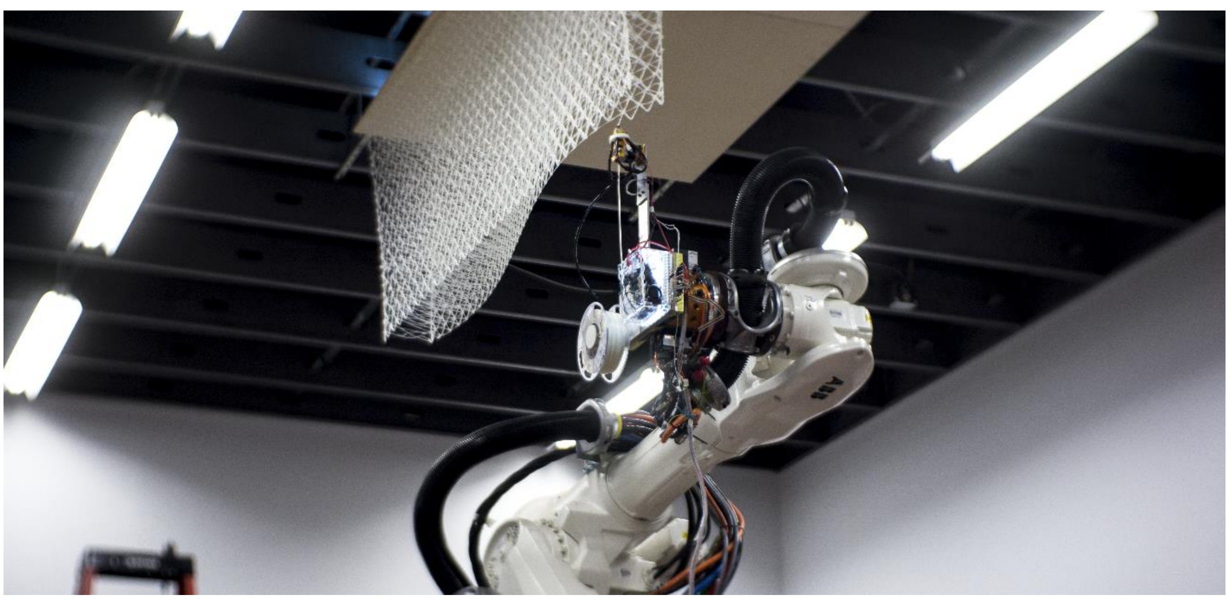
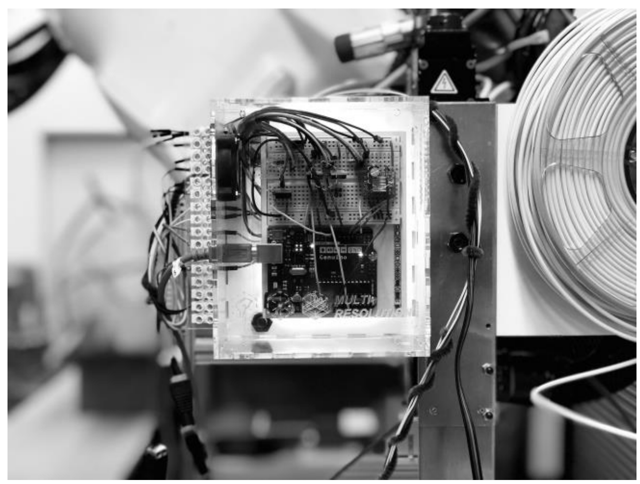


Figure 4. Ceiling retrofitting by FOAM process.

CHAPTER 2

Tool Fabrication for ABB IRB-6640 Robot

Design, fabrication and development of 3D robotic printing tooling



2.1 Machine exploration

Understanding the logic and mechanism before designing and fabricating a tool is efficiently effective. During much part of the beginning of the research, the acquisition of smaller scale 3D printing machines provided with enough knowledge for future fabrication steps. Prior researches have demonstrated that hacking regular 3D printers can provide with a faster printing process, speeding up the fabrication time up to 10 times compared to traditional layer-based printing (Mueller, Im et al, 2014).

All of the testing done to learn time and speed ratios were printed on Hatchbox Alpha 3D printer, a printer that activates the nozzle using six vertically actuated arms. This printer became an essential tool for the research, as all the nozzle protectors of the robotic tool are printed using ABS in this machine.

The natural next step was the acquisition of a 3D pen. Some wireframe structures were tested and prototyped to analyse flow rates, anchoring points over printed nodes and motion rates. This is not remarkably accurate as moving the hand a constant pace during the extent of the test is not natural. (Figure 5). Also, the control of straight segments was of a high value to later apply in the robot's toolpath process. Besides printing tests, opening the 3D pen was utterly useful to understand the mechanics of this process.

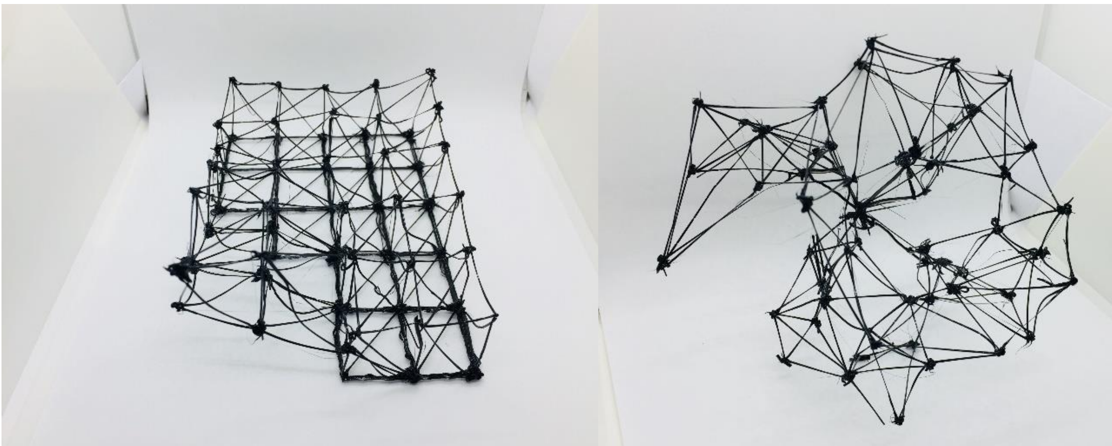


Figure 5. 3D pen wireprint test

2.2 Free Oriented Additive Manufacturing Equipment

This research explores the application of Spatial FDM in variable infrastructure conditions to break the standard horizontal stacking principle and introduces a novel Free Oriented Additive Manufacturing (FOAM) technique that adapts to more complex infrastructure conditions (Figure 4).

2.3 Tool compactness

Robotically Augmented Additive Manufacturing equipment consists normally of a material extruder system and a cooling system. The equipment is designed as a compact unit with all components directly attached at the EOAT to maximize freedom of movement (Figure 6).

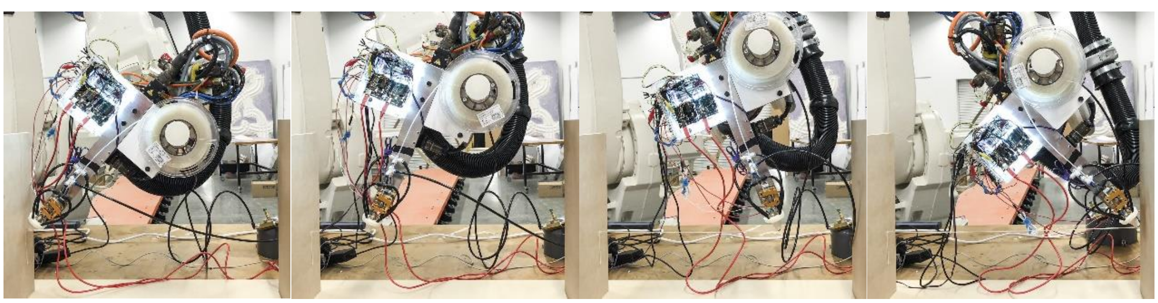


Figure 6. Tool compatcness

2.4 Tool components

2.4.1 Microcontrollers

Two Arduino Uno are used to control the two main parts of the process: temperature and feeding system.

2.4.2 Feeding system and Hot End

This research explores a commercial hackable approach. A regular 1.75mm diameter MK8 extruder is hacked so it can work for 3mm diameter filaments. The MK8 has the following characteristics:

Extrusion nozzle: 0.3mm
Material of Print: 1.75mm PLA/ABS
Flow rate of Nozzle: about 24cc / h
Sports shaft speed: 40mm/s
Voltage of heating nozzle: 12V
Thermistor: 100K NTC
Operating voltage of cooling fan: 12V
Heating rods: 6mm, 12V, 30W
Net weight: 450g
Normal working temperature: 190°- 230°

The melting point of the print media is compounded by a print nozzle and a heater mounted in an aluminium block. The hot end consists in regular commercialized aluminium barrels drilled with a slightly bigger drill bit than the orifice so it removes the Teflon tube that lives inside and breaks the capped end of the barrel. This allows to have a diameter of ~3mm, enough to make the 2.85mm filament pass through. The barrel is wrapped in Nichrome or stainless steel wire, with such diameter that provides with 12VDC 60W. This is enough to keep the nozzle to a melting temperature within the range of type of thermoplastics tested (PLA, PLA+, ABS, PETG). To make a longer nozzle, the join of commercial barrels is needed through a nut. This has the downside of not having the wire wrapped at the areas where the nut threads the barrel. This could be failsafed by wrapping the nut, although it won't provide with the same temperature at this area. This load is then charged on a 0.64mm Nichrome wire, which in order to work at 60W, it has to have a length of 800mm, having a resistance of 3.5 ohms, enough to achieve temperatures up to ~300C. This wire wraps a barrel in its total length to ensure a steady distribution of heat. Another type of metal has been tested, in this case, 0.33 mm thickness stainless steel wire. For the same resistance, a 1500mm length was needed.

Isolating the barrel is needed in order to keep the temperature stable. Due to the fact that the cooling system's hoses point at the end of the nozzle with enough pressure to drop the temperature at the totality of the length of the barrel, it needs to be safely wrapped by kapton tape (polyimide tape that supports high temperatures), and heating block cotton made from heat-resistant ceramic fiber. Last step is to protect the insulation layers from the cooling system with a windscreen. This windscreen has the support to connect the 4 teflon tubes that provide cool air coming from the pneumatic system. Numerous iterations have been done in this last apparatus, all of them, printed in regular 3D printers using ABS thermoplastic, as it supports higher temperatures than PLA. Results have shown that the distance between the air hoses and tip of the nozzle are best between 250mm to 500mm (Figure 7).

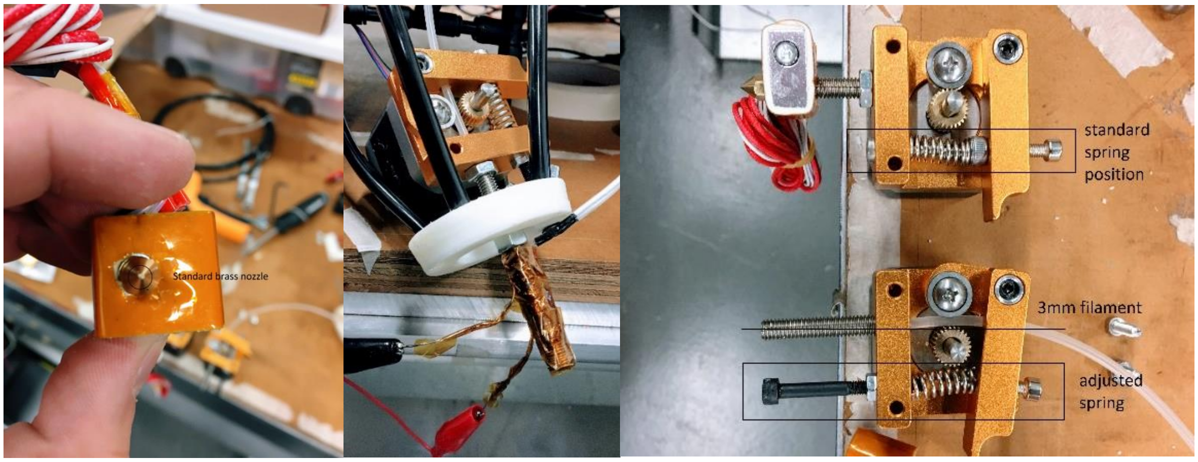


Figure 7. Commercial 3D printer MK8 hot end extruder

2.4.3 A4988 Micro stepper motor

An Arduino Uno controls the feeding system. As described above, a NEMA 17 commercial stepper motor was used to feed the nozzle. Between the Arduino code that send different signals that are translated into on, off, different ratio steps/time, and choosing the direction of the steps (counter-clock wise, or clock wise), we use an A4988 micro-stepping driver for controlling bipolar stepper motors, and has a built-in translator for easy operation. This means that it is possible to control the stepper motor with 2 pins from this controller, one manages rotation direction and the other controls the steps.

The driver has five different step resolutions: full step, half, quarter, eight and sixteenth step. Also, it has a potentiometer for adjusting the current output, over-temperature thermal shutdown and crossover-current protection.

Its logic voltage is from 3 to 5.5V and the maximum current per phase is 2A if good addition cooling is provided or 1A continuous current per phase without heat sink or cooling.

The eight-step resolution has demonstrated to work more accurately to the results we were looking for. The control of the feeding system is a negotiation between the driver resolution and the delay on the steps loop in the code of the Arduino board.

2.4.4 Temperature measurement

Adjacent to the barrel wrapped with Nichrome wire, a temperature sensor needs to be attached. Same Kapton tape used to isolate and to set the heating wire, is used to stick a Thermistor. This is a resistor that changes value (non-linearly) based on the temperature. The type of thermistor used is an NTC or *negative temperature coefficient.* NTC thermistors decreases resistance as temperature rises. Due to the fact that microcontrollers do not have a resistance-meter built in, but a voltage reader (known as an analog-digital-converter), converting resistance into a voltage is required. Adding another resistor and connecting them in series will work, so when the resistance changes, the voltage changes too, according to a simple voltage-divider equation. Keeping one resistor fixed is recommended.

For instance, if the fixed resistor is 10k and the variable resistor is R, the voltage output (Vo) is:

Vo = R / (R + 10K) * Vcc

Where **Vcc** is the power supply voltage (3.3V or 5V)

It is connected to a microcontroller. When measuring a voltage (**Vi**) into an Arduino ADC, the result is a float number.

ADC value = Vi * 1023 / Varef

Combining the two (**Vo = Vi**):

ADC value **= R / (R + 10K) * Vcc * 1023 / Varef**

If Vcc (logic voltage) is the same as the ARef, analog reference voltage, the values cancel out.

ADC value **= R / (R + 10K) * 1023**

Finally, **R** (the unknown resistance) is the result:

R = 10K / (1023/ADC - 1)

However, Arduino boards are naturally noisy, and interferences may vary the result, making it not scientifically accurate. An implemented solution is to use the 3.3V voltage pin as an analog reference. The 5V power supply comes from a computer's USB, making the signal noisier (as more than one task in parallel is being sent) than the 3.3V power supply (it goes through a secondary filter or regulator stage). An alternative is to take more readings and average them. This is especially useful as some readings fluctuate to some peak readings, out of a natural range. The effects are diminished with more readings.

In order to convert resistance to temperature, a simplified B parameter equation of the Steinhart-Hart equation is used.

$$\frac{1}{T} = \frac{1}{T_0} + \frac{1}{B} \ln\left(\frac{R}{R_0}\right)$$

Where:

To: 25C = 298.15 K (room temperature),
B: 3950 (Coefficient of thermistor),
Ro: 10Kohm (Resistance at room temp)

2.5 Cooling system

Cooling systems in spatial 3D printing methods are one of the crucial components to consider when designing this part of the tool. In this version of the tool, an ABS 3D printed ring-shaped object has been designed in order to hold the PTFE tubes coming from the pneumatic system of the robot through Digital Outputs. Due to the fact that the projected air points at the tip of the nozzle, a secondary layer of protection needs to be considered in order to protect the heated barrel from the air. A conic shape is incorporated to the ring as a windshield element.

Numerous iterations have been done in this last apparatus, all of them, printed in regular 3D printers using ABS thermoplastic, as it supports higher temperatures than PLA. Results have shown that the distance between the air hoses and tip of the nozzle are best between 250mm to 500mm (Figures 8,9,10,11).

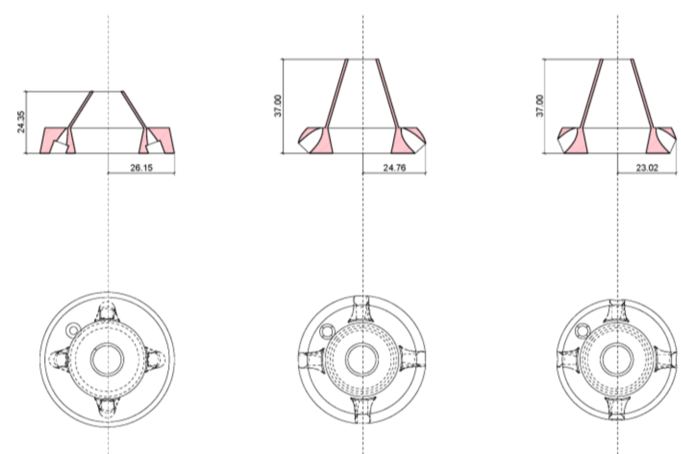


Figure 8. Air Cooling ABS 3D printed piece

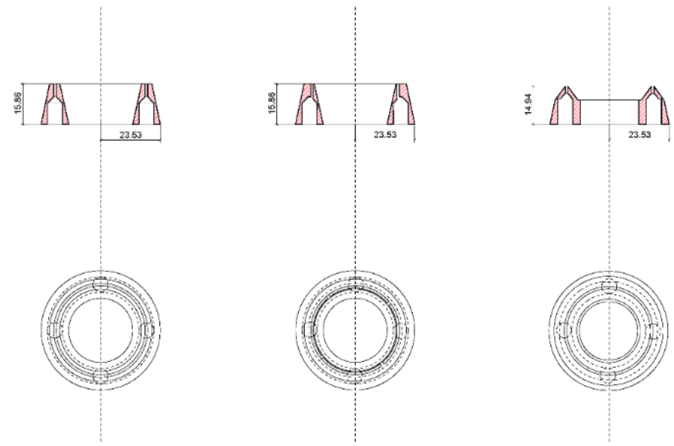


Figure 9. Air Cooling ABS 3D printed piece

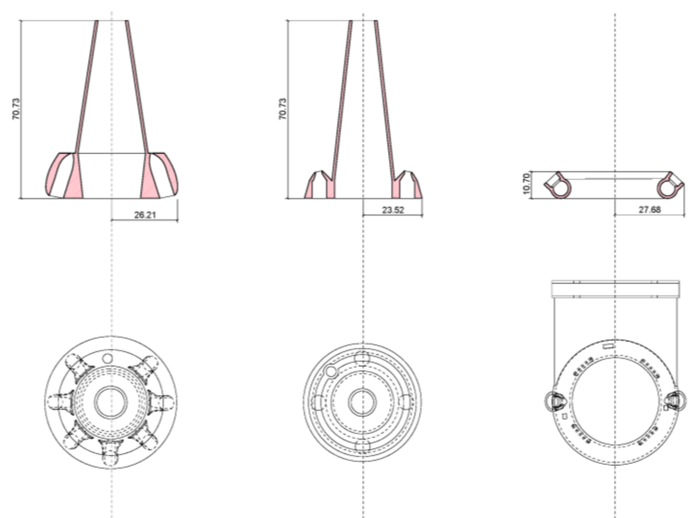


Figure 10. Air Cooling ABS 3D printed piece

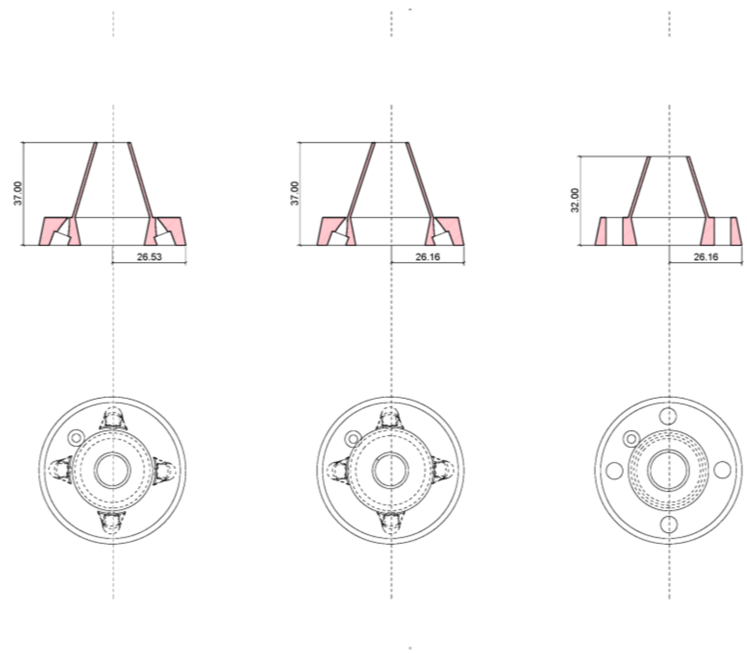


Figure 11. Air Cooling ABS 3D printed piece

2.6 Robot/Arduino communication

In order to coordinate and synchronize the functions of the robot and the Arduino, a communication between them is required. This is done through the DSQC 651, which is a circuit board normally mounted inside the robot controller, although it could also be mounted in an external I/O module. The combi I/O unit handles digital and analog communication between the robot system and any external systems (more information can be found in the 3HAC020676 ABB IRB6400TR official manuals).

I/O stands for Inputs/Outputs. Given the time for this research, only digital inputs are used, in other words, the communication only happens in one direction, from the robot to the Arduino. The wiring is made through an ATI QC-110 plate. Particularly, the interchange of information between both machines is directly related to the geometrical information at both scales, meso and micro scale. The robot is drawing the geometry, therefore, it has information about the location of each target. This means that depending on the direction of the printing path, the stepper motor should act accordingly. For instance, if it is printing upwards, the velocity of the stepper motor should be slightly slower than the motion of the robot to tense the segment. On the contrary, printing downwards might require quicker steps.

The robot emits electrical pulses with different lengths that are related to the target position, thus, to the geometrical pattern. The Arduino then receives this pulse, and interprets it accordingly, actuating the motor. Is critical to work with ranges instead of fixed values, as naturally, this communication is noisy enough to make the transmission not legible. This research works within ranges of 10000 microseconds. Among the totality of instructions, there are: slow extrusion, quick extrusion, stop or reverse. Arduino's circuit schematics of the control of stepper motor shown at Figure 12.

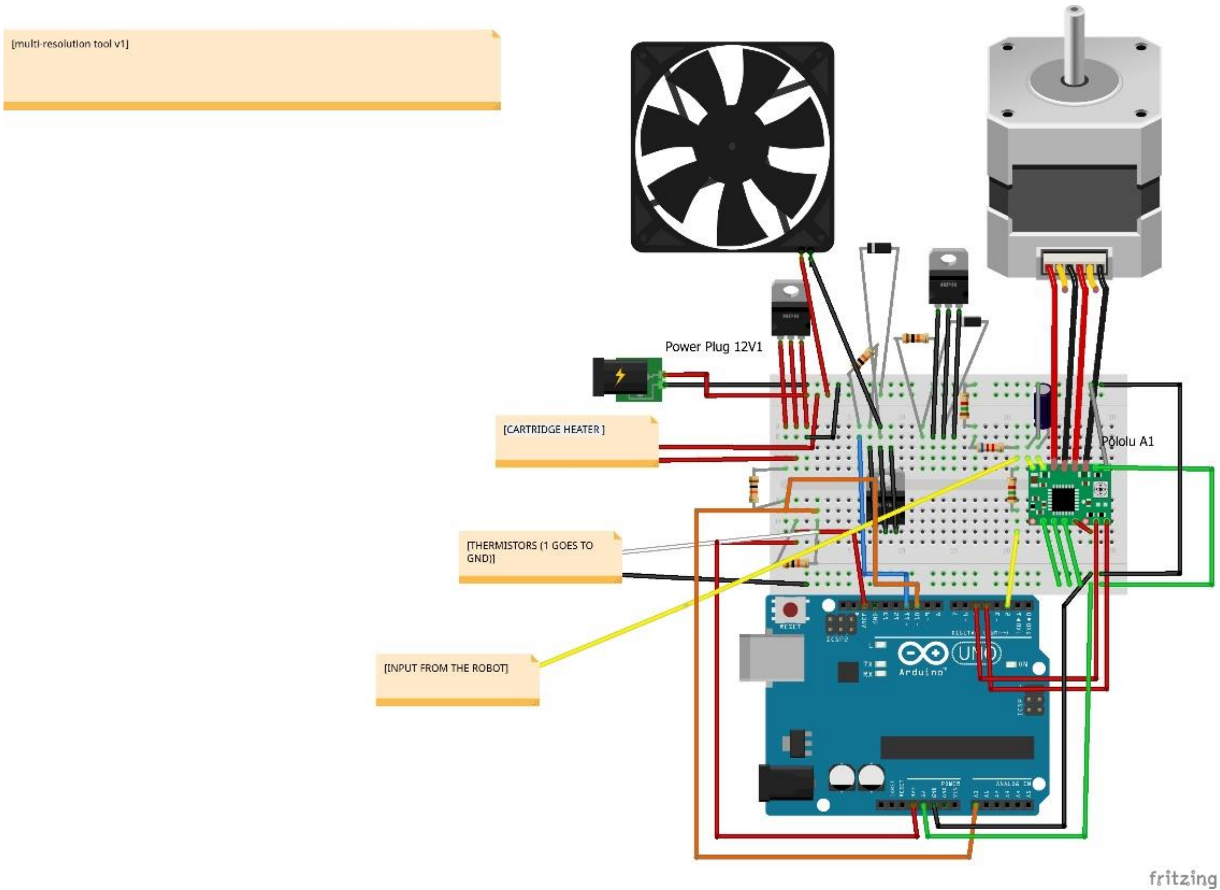
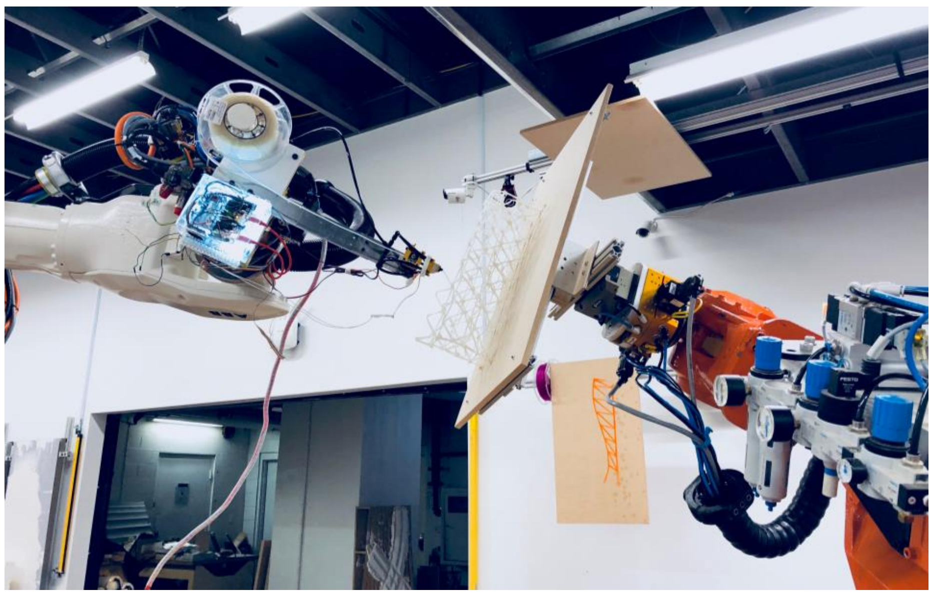


Figure 12. Stepper motor Arduino Schematics

CHAPTER 3

Free Oriented Additive Manufacturing Method

Design, fabrication and development of 3D robotic printing tooling



3.1 Background

Fused Deposition Methods has demonstrated its usability as a technology for small scale fabrication. Variations of normal fused deposition methods that consist in a layer by layer approach are those consisting in extruding filaments in the space, in which the plastic is molten and solidified in the air connected normally by nodes. This approach is an alternative that potentially permits the building of lighter structures at a reduced cost and time (Mueller, Inn et al, 2014). Examples of this approach has been primarily studied at the ETH, Gramazio Kohler Research or at The Bartlett School of Architecture, UCL.

This thesis explores the fabrication through this method, using different type of materials, such as PLA, PLA +, PETG or ABS. Thermoplastics are commonly used in this method as they require minimal heating energy in order to melt (Table 1).

Table 1: Thermoplastic Print Temp

MATERIALS (temp)		
	ABS (230-250C)	PLA+ (205-260C)
	ABS+ (220 - 260C)	PETG (230-250C)
	PLA (180-250C)	PVA (180-210C)

3.2 Printing discreteness

This research explores two methods of printing. In study cases I and II, the research takes a directional 2D approach based on patterns that lie on a surface. This means that this method prints based on layers, distributed in such means that in order to form a volume, the orientation of these layers should change. For instance, layers in a positive X direction crisscrossed with layers in positive Y direction. In study case III, the approach is rather different. Research studies 3D patterns that exist in a given cubical volume. Instead of organizing a series of surfaces to make a volume, this approach discretizes a given general volume into smaller fragments.

3.3 Spatial extrusion

Although some large scale length tests have been tested (Figure 13), for most of the study cases, short rectilinear segments are chosen in order to design and fabricate. The process starts by setting the temperature of the nozzle at a temperature that melts the filament. The robotic arm moves the nozzle following a given toolpath. While this technique allows a high degree of freedom of movement, there are some constrains. For instance, printing vertical from top to bottom is not possible as the nozzle would collide with the filament printed. This would be different when printing upside down over existing infrastructures. The direction and taper of angles are directly constrained by the angle of the nozzle. For study case I and II, the toolpath follows a 2D version of the octet-truss patented by Buckminsterfuller in 1961 (Ashby, Deshpande and Fleck, 2001). This is a triangle-pattern that forms layers of trusses. In order to add a higher structural strength and continuity at the nodes, the triangle is broken at its vertices to short horizontal lines that provide with more support for upper layers to connect with. The logic of the pattern would be the following: lower horizontal segment – diagonally upwards segment – horizontal higher segment – diagonally downwards segment.

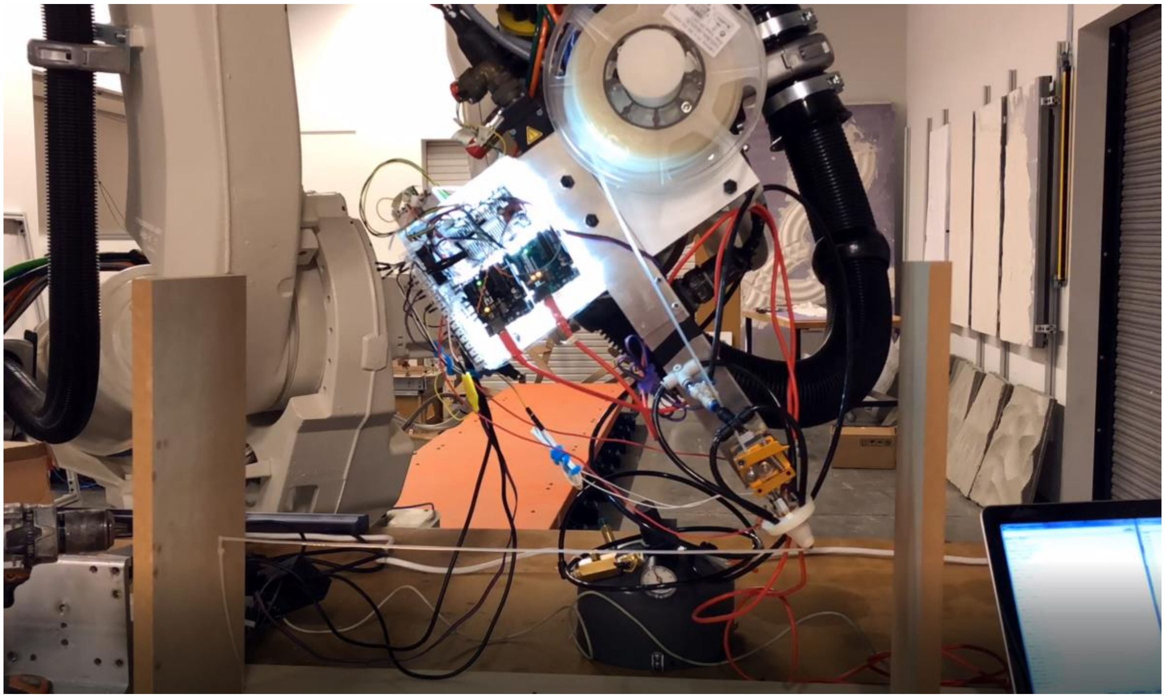


Figure 13. 1m length cantilever extrusion test

3.4 Temperature

One of the critical factors that intercede in a consistent extrusion is the control of temperature. For this, a Proportional – integral – derivative controller (or three term controller) is used to get a desired temperature. This is a widely used mechanism used in industrial control systems. A PID controller continuously calculates an error value e(t) 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.

This research has explored two different methods that are used as PID controllers. The first one is a standardized commercial PID, bought in Amazon. Normally, this type of controllers use a thermocouple sensor (type K) to measure the temperature of the nozzle. The second and most used approach in this research takes an Arduino Uno with a PID algorithm coded in it. Instead of a thermocouple, this approach works better with Thermistors.

The signal that the Arduino outputs is converted through a metal-oxide-semiconductor field-effect transistor (MOSFET), which is a type of field-effect transistor (FET). It has an insulated gate, whose voltage determines the conductivity of the device. In order words, it is used as a gate that controls the amount of power (Watts) that is loaded at the output wire. Other mechanism can be used, such as a solid-state relay (SSR). This is an electronic switching device that has no moving parts (it does not wear out, to the opposite of electromechanical relays). Using a SSR, the control signal must be coupled to the controlled circuit in a way which provides galvanic isolation between the two circuits. The type of SSR used in this research utilizes optical coupling. When it switches on a photo-sensitive diode turns on a back-to-back MOSFET to switch the load. Both methods have been tested, getting more stable results using the solid-state relay.

3.5 Feeding system

Another crucial system in order have consistency while printing is the motor that feeds the filament into the nozzle. The flow rate the stepper provides must be in sync with the motion of the robotic arm. The toolpath segments must correspond to a different feeding speeds depending on the direction of the toolpath. For instance, if a horizontal segment is being printed, and it represents the connection with the base or prior printed segments, the motion of the robot should decrease while the ratio steps/time of the stepper motor should increase. When printing vertically, the motion of the robot should be slightly bigger than the feed rate, as it would create tension in the segment, avoiding sagging effects. When printing the end of a vertical or diagonal segment, the robot must wait to provide with enough time cooling the filament in order to continue. Depending on the situation, the stepper must continue feeding the filament at a small rate, or should stop the extrusion (if the current node is the end of a continuous segment or the following segment is shorter than the previous one).

3.6 Solidifying filament

The third crucial aspect during the fabrication process is the transition of molten to rigid state. A cooling system is needed to be able to make this process happen at the same time as the printing is happening. For this system, we use the pneumatic system the robot has internally to inject air at a desired pressure. This variable becomes really important to master as minor changes produce major consequences and therefore, undesired geometries that has little fidelity with the design process. Many iterations have been analyzed and prototyped. A four tube air injection is chosen, at 30 mm distance from the TCP (Tool Center Point).

3.7 Tool Orientation

The tool is taught in ways that the Z elongation of the tool definition is perpendicular to the ground, being the ground the Work Object base, normally, with positive Z pointing up, following the right hand rule.

For large scale prototypes and test, the tool has been inclined generally when working with more than one work object, and normally when the tip of the nozzle had to touch ground conditions, avoiding self-intersections.

Although for each of the three case studies, the extruder has always been positioned perpendicular to the work object, in parallel ongoing study cases, the tool is being tested tilted.

3.8 Printing tests

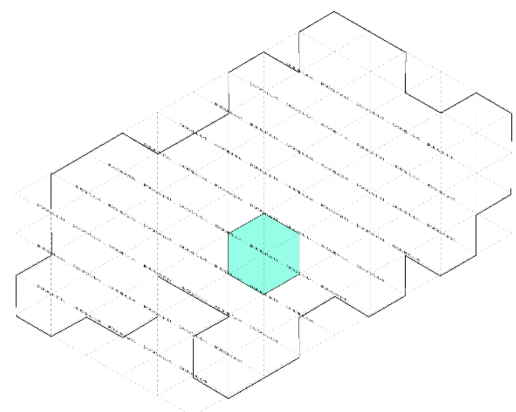
Prior to any case study, an extensive printing test process was studied and analysed. A squared spiral alike geometry was used as a testing case, as it had corner conditions (a 90 degree corner demands a high fidelity in order to keep the geometry in place), and a combination of upwards and horizontal segments. This case did not test downwards segments (Figure 14).

Figure 14. Printing tests changing variables

CHAPTER 4

Computational Resolution-based Methods

New design methodology through discrete computational methods for Free Oriented Additive Manufacturing



4.1 Overview

This research proposes a new methodology of design based on resolution adjustments. In four case studies, two distinct approaches are taken. For case studies I and II, the design approach studies how to apply a printable pattern with a mono-resolution focus. This is a 2D directional approach in which a 2D pattern builds up a lattice. In case study III, the algorithm explores a multi-resolution design approach in which different scales, 3D patterns and materials constitute a bespoke architectural element that respond to the demands of the user. The application of a multi-resolution based design technique provides with a biased distribution of materials, density and geometries that make possible the adjustment of an architectural element to specific budgets.

A description of different computational methods of design and fabrication based on resolution differentiation that are specifically arranged to support FOAM techniques is presented (Table 1). These methods are applied in several fabrication workflows to demonstrate viable and alternative solutions of construction using the same robotic work cell. Four Case-Studies with different workflows (Table 2) are implemented to:

- Illustrate a broad applicability of Free Oriented Additive Manufacturing.
- Achieve a wider understanding of the inherent constraints of the technique.
- Explore the possibilities of introducing the technique in an automated construction environment providing bespoke production process given existing infrastructures.

Table 1: Computational Methods

	Method A	Method B
Resolution	Mono-Resolution	Multi-Resolution
Material	Single Material	Multi-Material
Algorithm Logic	2D Lattice Based	Octree Voxel Based
Strategy	Bottom-Up Design	Top-Down Design
System	Continuous	Stereotomic & Continuous

Table 2: Cell Components of Fabrication Workflows

	I: One to One	II: One to various	III: Two to Various
Robot (reach, m)	ABB IRB 6640, (2.55)	ABB IRB 6640, (2.55)	ABB IRB 6640, (2.55) ABB IRB 4400, (1.96)
Work object	Static work object	Three static work objects	Dynamic work object
Dimensions (meters)	2.30 x 1.10 x 0.012	0.70 x 0.35 x 0.012	0.70 x 0.35 x 0.012
Material	MDF	MDF	MDF

4.2 Discretization processes

The strategy in which this research bases its foundation explores discrete methods of digital design. MIT professor Neil Gerschenfeld makes a distinction between analogue and digital organizations (Gerschenfeld, Carney et al, 2015). According to prof. Gerschenfeld, analogue data is continuous while digital data is discrete. Analogue systems present bondless connections possibilities, whereas in digital systems, a piece of matter has a limited number.

Under this paradigm, this research proposes a new methodology of design based on resolution approaches. A workpiece (this research explores architectural elements, that is, in this case, a wall) is discretized in as many smaller units as deemed necessary (constrained by physical and computational limitations), in which each single discretized unit of a geometrical piece is analysed and designed according to direct necessities or demands from the user. This analysis is a holistic process in which the whole discretized piece takes more importance than the micro-scale of the unit, being the result of a negotiation between the two scales of design, micro and meso.

A hypothesis is that we might re-adjust and deliver bespoke architecture through the use of a multi-resolution methodology of design and fabrication, which distributes, chooses and designs *arxels* (discretized units of the global workpiece) at a micro scale. Due to the fact that computation and fabrication is closer than ever to architects, we have access to design at a micro scale, thus, the ability of hyper-tailored architecture at different levels of resolution.

Through changes in resolution, the same element that a priori might exceed budget limitations, could be re-design, lowering its resolution (through different material or changing the size of the unit), changing materials, tweaking the geometrical unit (pattern) or adjusting density, could be fabricated within the budget limits, with minor changes in its global meaning.

This research assumes that new sensibilities will appear and are necessary in order to design and provide with an insightful architecture. As this method of design manages a large amount of data, this might not be expressed through plans, but through pages of information. Communication is, therefore, data-based instead of drawing-based. This process is embedded in a holistic system summarized in three steps: design information – design algorithm – fabrication data. (Figure 15).

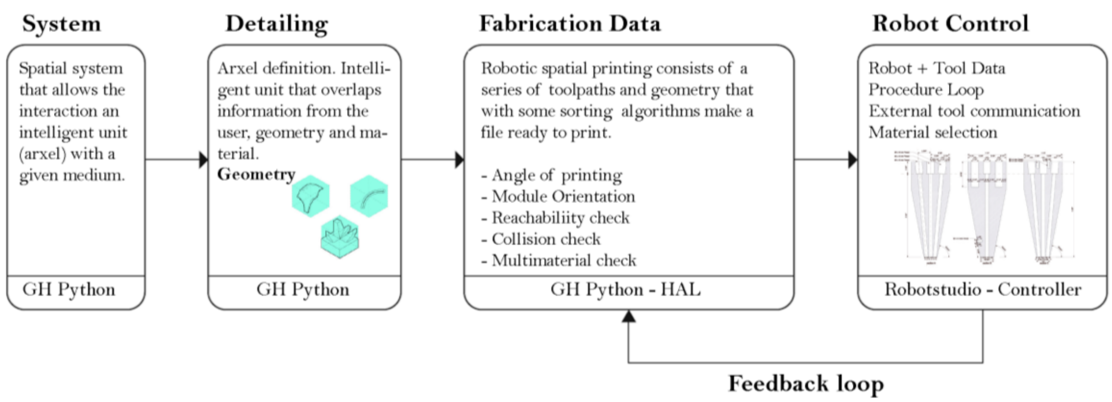


Figure 15. Holistic system

4.3 Computational Method A: Digital Mono-Resolution

This method consists on a bottom-up 2D lattice-based computational approach which builds a lattice based upon the application of a printable pattern with a mono-resolution focus. The pattern is designed as a repetition of the sequence: short supporting segment – diagonal downwards segment – short supporting segment – diagonal upwards segment. This system follows the logic of the 'sweep1' Rhinoceros command (Figure 16.1), outputting a 2D lattice built upon a designed pattern cell (Figure 16.2), therefore, creating a geometry from a bottom-up approach rather than mapping a pattern onto a surface. A minimum of two set of guide curves are needed in order to create a volumetric structure, for instance, a wall (Figure 16.3). Consequently, the algorithm computes a necessary weaving technique which connects the nodes of lattice A with the nodes of lattice B. (Figure 16.4).

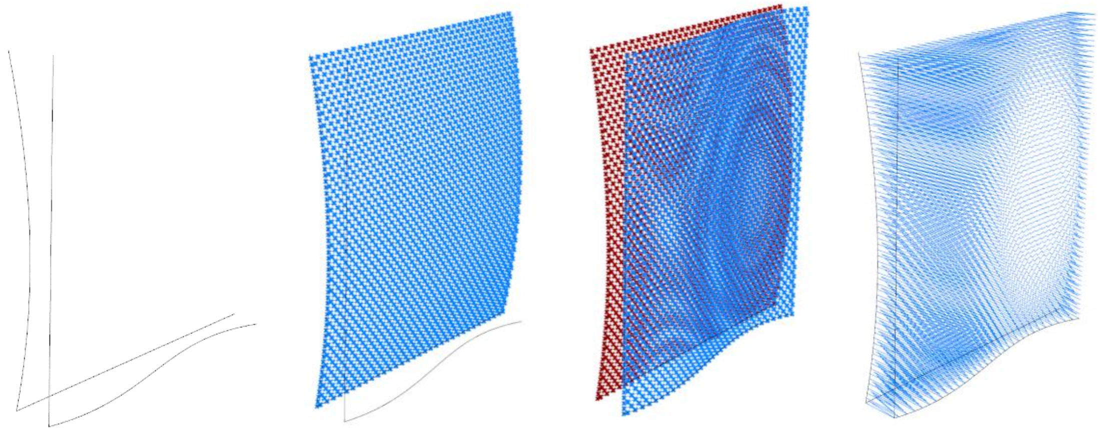


Figure 16.1, 16.2, 16.3, 16.4. Process of the computational algorithm A.

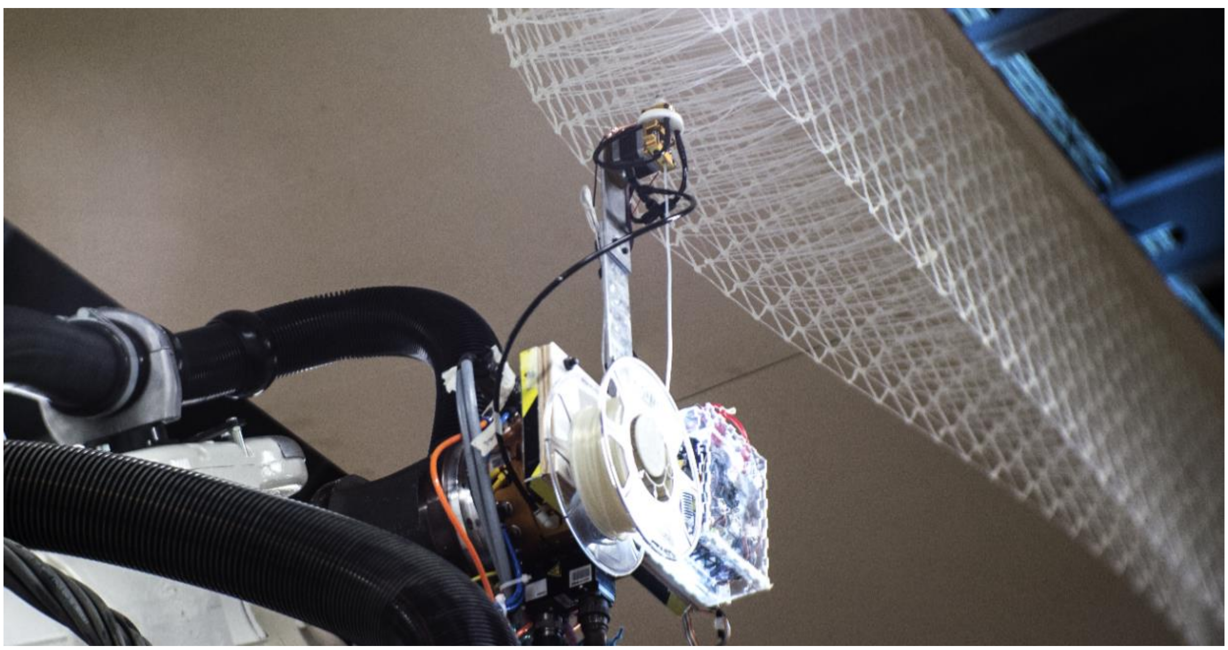


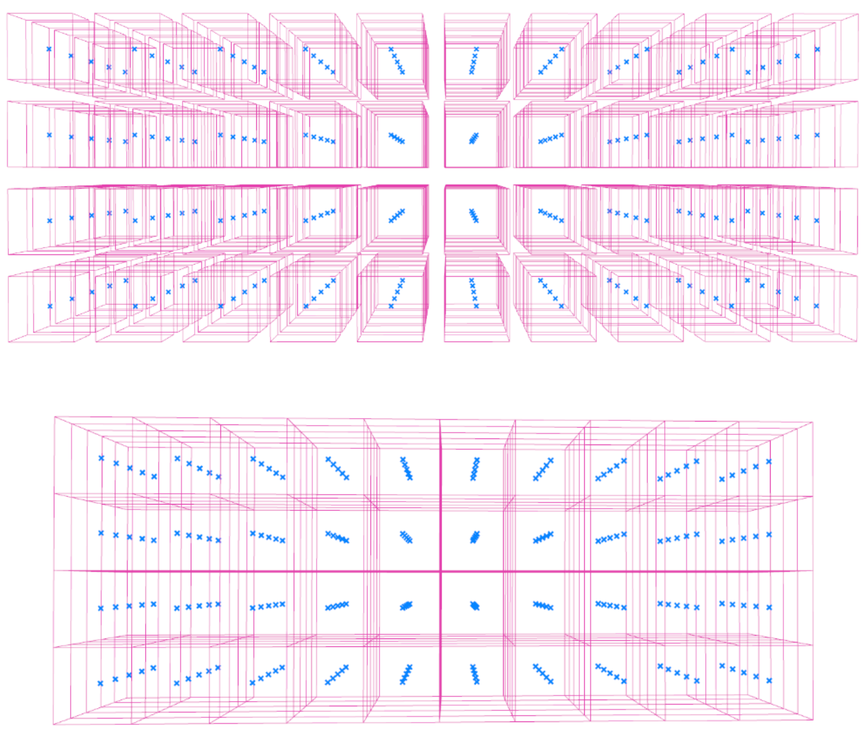
Figure 17. Detail of differentiated spatial lattice Work Piece.

4.4 Computational Method B: Digital Multi-Resolution

A top-down discretization logic is followed. Similar to a voxel-like structure, this method takes a geometry and registers every single unit cell given a resolution size. Initially, an underlying grid stores information about the position of each cell in relation to the geometry, distinguishing between cells that live inside, outside or at the boundaries of the geometry.

4.4.1 Voxel - 3D Grid

To discretize the space, an underlying grid that acts as a potential container of information is coded. As initialization parameters, a 3D grid has a cubical size, which means that the plane XY of the voxel has same measures as XZ and YZ planes. The size of each of the voxels of the grid will be constrain by the tool used to fabricate the element. For instance, in case study III, a grid of voxels of 30x30x30mm is used. We couldn't initialize the spatial grid with smaller voxels as the nozzle would collide with an already printed geometry within the same voxel. The grid is also capable of having different controllable size of voxels, in similar manners that an octree algorithm works. For flexibility purposes, the grid is able of offset to both, outside or inside, so, if the grid is offset towards outside, the cells wouldn't be touching each other. On the opposite, if the grid is offset towards the interior, the cells would have some overlap. The direction of the offset can be controlled, so it does not necessarily mean that the offset happens uniformly at the 3 directions (X, Y and Z). This characteristic could failsafe fabrication issues (i.e. the height of the geometry at each *arxel* might not reach the desired Z due to material deformations, so a slight overlap in the Z direction would benefit *arxels* at the upper level, as they would be anchored to the top part of below floors).(Figure 18).



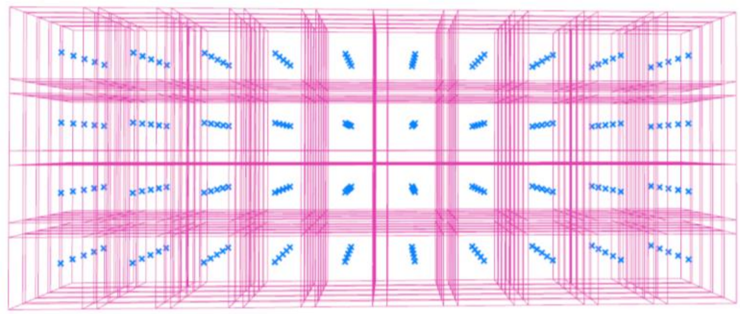


Figure 18. Flexibility of the grid system. The image at the upper part shows positive offset, while the image at the bottom shows negative offset, therefore, overlap. The image at the middle is a zero offset grid

4.4.2 Arxel©

A unit of the grid system that lies inside, outside or at the boundary of the geometry of analysis, it becomes an *arxel*, as it contains digital data. In other words, the difference between a voxel and an *arxel* is that when a grid is interacting with any given geometry, the unit is called *arxel* as it has architectural properties (Figure 19). An *arxel* is an intelligent unit of information that overlaps agendas of materiality, economy and geometry with performance data such as structural behavior, opacity, or density level. Given that we can computationally represent variations of information within the spatial grid confined to single finite units, and given that we can assign material and geometric properties to these units that define the design, the distribution of performance pairs with the distribution of properties.

The encouraging hypothesis is that if a bounded digital unit of representation (pixel, voxel, etc) has the ability to encompass an aggregation of related data that respond to different conditions such as density, opacity or structural properties, then an algorithm might be able to match this conditions to the particular constrains of each arxel at every single location within the grid (Oxman 2010).

As a rule of design, a unit of the spatial grid that has no information in it (empty units), generally receives the name of "Voxel". On the contrary, when a voxel has information in it, it becomes an "*Arxel*"©. The name "*Arxel*"© is based on a contraction of *"arx"* (architectural) and *"el"* (element). Similar formations with *"el"* for "element" include words pixel, voxel and maxel (Oxman 2010).

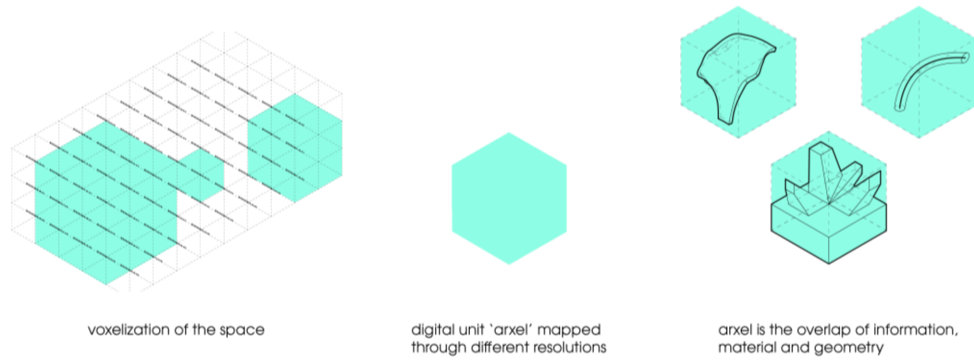


Figure 19. Grid-Arxel relation

4.4.3 Arxel properties

An *arxel* may contain as much information as the capacity of the computer that process the algorithm. The array of information is constantly updated so the user and designer are aware of it at any moment in the process of the design. Some properties that an *arxel* can have are: material, size, volume, length, density, opacity, location, structural information, color, etc.
As a result, an *arxel* is not measured by only one measurement unit, but multiple ones. For instance:
An *arxel* is measured in mm when responds to properties of length.
An *arxel* is measured in grams when responds to properties of weight.
An *arxel* is measured in % of volume filled when responds to properties of opacity.

Table X: example of information of two adjacent arxels

INDEX	(i,j,k)	(1,8,2)	(1,8,3)
CONDITION		In	Boundary
MATERIAL		PLA	PLA+
LENGTH	(millimetres)	163.90	90.90
PATTERN		Type I	Type III

4.4.4 Nomenclature

The design of a new nomenclature becomes relevant when the piece is analyzed globally at a meso-scale. The number of different shapes an *arxel* can take depends on the degree of specificity of the fabricated piece (Figure 20). Future optimization algorithms will determine whether a set of geometries is optimum or need variation. This approach is not yet implemented.

For Case Study III, a single unit can have four degree of variations, which correspond to the four 90 degrees rotations over the XY plane. Rotation transformations play a critical role, as it is the driving force that determines whether an *arxel* is printable or not. At the same time, the same *arxel* can have different structural properties depending on its orientation. For Case Study III, the unit has been analysed from a material property perspective. It means that depending on the rotation, the same unit can express different levels of opacity at a global scale.

Figure 20. Arxel nomenclature in the Multi-Resolution algorithm.

4.4.5 *Arxel* associations

The *arxels* that conform a discretized bigger entity act as a group of neighbors. There is physical continuity between units that make the piece be read as a unitary element composed by various units of information and fabrication. In case study III, a single unit can have four degree of variations, which correspond to the four 90 degrees rotations over the XY plane. Rotation transformations play a critical role, as it is the driving force that determines whether an *arxel* is printable or not (Figure 21, 22).

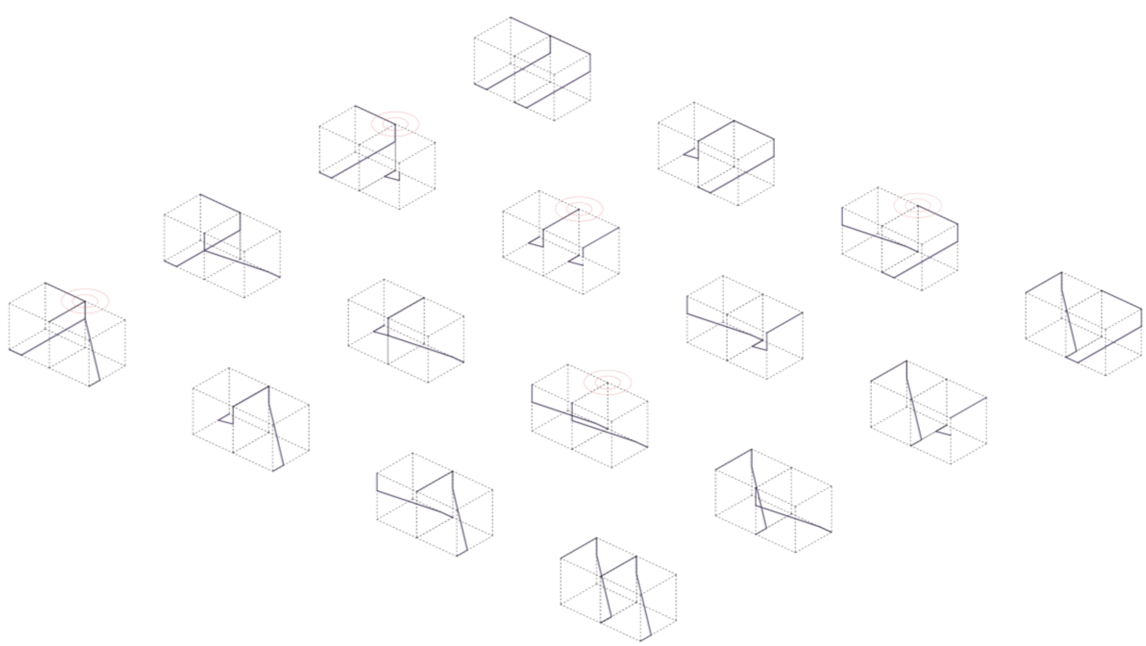


Figure 21. Printable associations of Pattern I

Figure 22. Printable associations Pattern I and II

4.4.6 Designing with a Multi-Resolution approach

This design method studies the possibility of adjusting a given element to specific conditions through the application of a multi-resolution concept. Multi-resolution is used by means of applying a higher resolution at interesting areas, while lowering the resolution at less interesting areas. Resolution can be achieved by a negotiation between materials (PLA, PLA+ and concrete have been tested), density, geometries (patterns) and scale (algorithm follows the logic of an octree approach).

The design approach starts by specifying an approximate overall shape of the element to be designed. The volume of the piece is computed so the user is ready to set up the main level of resolution. This will depend directly on physical restrictions coming from the fabrication tool. A function classifies every voxel of the grid, distinguishing three states depending on the location relating the workpiece: inside the overall shape, at the boundary, or lying outside the piece.

The cells are given with as many different geometries as the user may deem necessary. Normally, the first clear distinction between cells, which is where they lie on the grid with regards of the surface, happens in the differentiation of the geometrical pattern the *arxel* has. Those cells lying on the surface will generally have a different pattern than those lying inside the volume of the surface.

Following the demands of the end user, the algorithm starts placing the set of geometries taking into account the set of possible transformations each pattern has, depending on a list of priorities. If the user has a limited budget, the algorithm will find a combination to satisfy the overall representation of the inputted surface. To satisfy the design and construction of the surface with less material than a priori, the surface needs, the cells will lose resolution by means of:

1. Choosing patterns that require less material quantity.
2. Scaling up cells so the degree of detail decreases.
3. Changing the material of the *arxel*.
4. Culling out *arxels* that do not play an important role in the overall structure

If the user prioritizes some opacity differentiation, or instead, there is a preference for structural behavior, the algorithm will find an accurate solution with the given set of *arxels*.

There is an important fact which is when the algorithms reaches the exhaustive level. At this situation, the algorithm has not been able to reach a valid solution (within printable solutions). A negotiation of what external piece may be injected in a specific location is open between the users and designer.

There are some considerations in order to design through Multi-Resolutions approaches:

1. The design at micro-scale: The design of the patterns play a main role in the overall system. At the moment of designing, one must take into consideration further constrains down the road like physical fabrication constrains (i.e. self-collisions, material, dimensions).
2. Aesthetic layers might be imported at a meso scale. Multi-material systems allow for variability in colors (proper of the material).
3. Errors of the system are taking into the equation, so they become a design opportunity.

4.5 Algorithms for fabrication

A tectonic design approach knowing the affordances and limitations of the material along with a tool design approach, which takes into account the limitations of the fabricating tool are recommended when using this technique. However, anticipating constrains does not ensure a clean and failsafed fabrication process. The feedback loop between design and fabrication processes actuates in order to prune unforeseen problems. The main challenge in spatial printing is that the nozzle has to respect already printed material in order to prevent collisions. About half of the algorithm code are definitions that deal with fabrication constrains. For instance, in the algorithm used for case study III, a detector for collisions should be checked between *arxels* (this is, between the last point of an *arxel*, and the beginning point of the following *arxel*). In order to be efficient, instead of particular checks, simply an offset in the Z direction, higher than the height of the *arxel*, is given at the first and last points. This ensures that we never collide with already printed geometries during traveling. For case study I and II, this same definition is applied at the end of each row. (Figure 23 and 24)

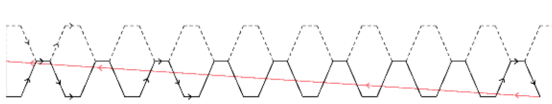


Figure 24. Toolpath without avoidCollision definition

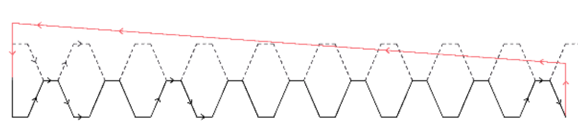


Figure 23. Toolpath with avoidCollision definition

At a micro-scale (pattern scale), another consideration needs to be taken. Same logic as the example above is followed. However, in order to be efficient, this is taken at the time of the design of the pattern, so future feedback loops are avoided. The taper of the nozzle establishes the first constrain when designing a pattern. For instance, two vertical segments must have a separation that equals the width of the nozzle. Another example, while it is always possible to print upwards or horizontal (regardless direction, angles), printing downwards become impossible when the slant of the print is steeper than the taper of the nozzle. (Figure 25)

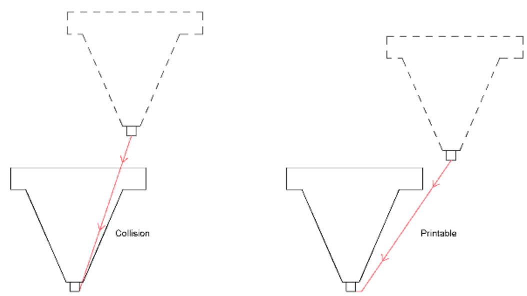


Figure 25. Collisions nozzle-already printed material

A higher degree of complexity is presented in the multi-resolution algorithm. Besides above considerations, multi-resolution algorithm, due to the nature of the arrangement of the patterns into cells, that are in touch with its 25 neighbor cells (8 at the same floor, 9 on the upper floor, 9 on the floor above). To have variety and design with parameters of opacity, structure or noise, each pattern can be rotated respect the XY plane. Each pattern then has 4 variations, thus, 64 possible matches. If another pattern is used, this multiplies exponentially the possibilities. Because it would become really expensive to design the patterns a priori, having into mind the array of potential collisions, a set of definitions that deal with this complexity is used. Given a set of different patterns, it allocates only printable adjacent patterns, respecting rules of opacity or structure. (Figure 21)

4.6 Robot toolpath

To finish the computation process, a robotic fabrication toolpath needs to be coded in order to make the geometry printable. In regular 3D printing processes with standard 3D printers, the fabrication file is first generated by converting the model into an STL file format (an abbreviation of Stereolithography), which describes a given geometry in a raw, unstructured triangulated surface by the unit normal and vertices of the triangles using a three-dimensional Cartesian coordinate system. Then, a 3D printing generator, normally open source software such as Slic3r, SuperSkein, RepRap Host Software, take a given STL file and generates a G-Code file (i.e., the instruction language used by 3D printers) for the production of the 3D modeled object.

The fabrication methodology involves robotic fabrication, making the generation of the fabrication file take an alternative ways. Specifically, this research uses the ABB IRB 6640 robotic arm, situated at the digital fabrication lab (dFAB), at the Carnegie Mellon University School of Architecture (Figure 25).

Specification

Robot version IRB	Reach (m)	Handling capacity (kg)	Center of gravity (kg)	Wrist torque (Nm)
IRB 6640-235/2.55	2.55	235	300	1324
IRB 6640-185/2.80	2.80	185	300	1206
Extra loads can be mounted on all variants 50 kg on upper arm (except ID) and 250 kg on frame of axis 1.				
Number of axes	6			
Protection	Complete robot IP 67			
Mounting	Floor mounted			
Controller	IRC5 Single cabinet, Dual cabinet			

IRB 6640

Axis movement	Working range	Axis max speed
Axis 1 Rotation	+170° to -170°	100 to -110°/s
Axis 2 Arm	+85° to -65°	90°/s
Axis 3 Arm	+70° to -180°	90°/s
Axis 4 Wrist	+300° to -300°	170 to -190°/s
Axis 5 Bend	+120° to -120°	120 to -140°/s
Axis 6 Turn	+360° to -360°	190 to -235°/s

A supervision function prevents overheating in applications with intensive and frequent movements.

Figure 26. Abb IRB 6640 Specs

ABB uses RAPID as a high-level programming language to control ABB industrial robots. The fabrication code, which is a combination between Arduino functions and ABB robot functions (this generally entails motion instructions such as moveAbsJ, moveJ or moveL commands, and inputs instructions that controls features such as pneumatic system, electric system, and any added system a robot might have). For this research, only pneumatic and electric system are used. Various methods can be taken in order to write a module that contains procedures and definitions that actuate the robot.

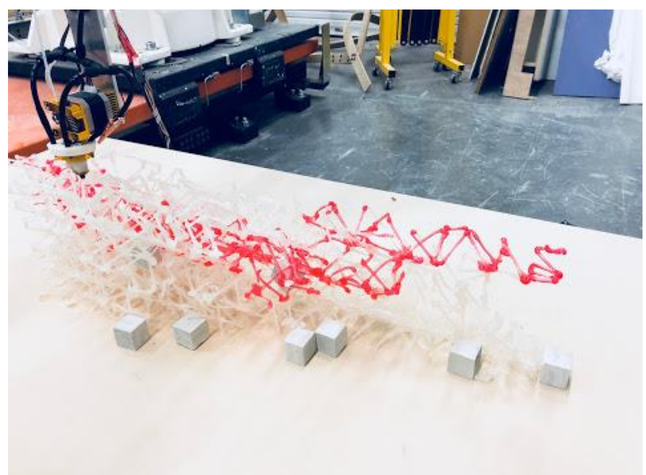
1. **On-line programming**: this is, using the IRC5 Controller (or teach pendant). It is the most popular method of robot programming. According to the British Automation and Robot Association (BARA), over 90% of robots are programmed using this method. The logic of this program can be generated using either a menu based system or simply using a text editor. The main characteristics of this method is the means by the robot is taught the positional data.
2. **Off-line programming:** this method is also known as simulation. It ensures that advanced control algorithms are operating correctly before moving them onto a real robot. It is also used to improved efficiency, as it allows a much faster re-configurability condition. Similar to the way in which CAD systems are being used to generate NC programs for milling machines it is also possible to program robots from CAD data.

This research uses both methods with clear distinct purposes. The on-line method is used to teach tools and work objects. Setting the home position as a house keeping procedure is also taught here. For the rest of the operations, an off-line approach is used. There are a variety of software that can be used to off-line program robots. ABB has its own software, RobotStudio, which is highly recommendable, as it is 100% reliable when checking the kinematic solvers and collisions. However, a perhaps easier alternative is the use of HAL plugin for Grasshopper, Rhinoceros. Introducing the data of the robot, track, as well as tool, work objects, with the addition of adding meshes in some components to have a higher fidelity (in simulation purposes), and reliability, this software does the engineering behind to solve the configurations, and therefore, providing with the fabrication file in RAPID language. While this could be sent directly to the controller, bypassing RobotStudio software, this is extremely discouraged, as sometimes HAL does not detect internal collisions nor configurations.

CHAPTER 5

Case Studies

Concept proving through four study cases



5.1 Introduction

Three study cases have been tested as procedures to prove the resolution based design methodology explained above. First and second case studies deal with a mono-resolution approach in a way that the first one tests a mono-resolution based printable algorithm and the second tests the influence of physical conditions over the same geometry, such as gravity and work object orientation, and the synchronization of a multi-robot workflow. The third study case implements the algorithm of multi-resolution, which validates the proposed methodology. The four study case introduces large-scale linear extrusion method.

5.2 Case Study I: Digital Mono-resolution. Continuous approach

This case study applies the computational method A and the fabrication workflow I. The aim of this case is to test FOAM at an architectural scale. This is manifested through the design of a 2x1m curvy wall that presents different curvatures at each side of the wall, varying its global thickness. This workpiece is printed upside down, hanging from an existing structure at 4.00m high ceiling.

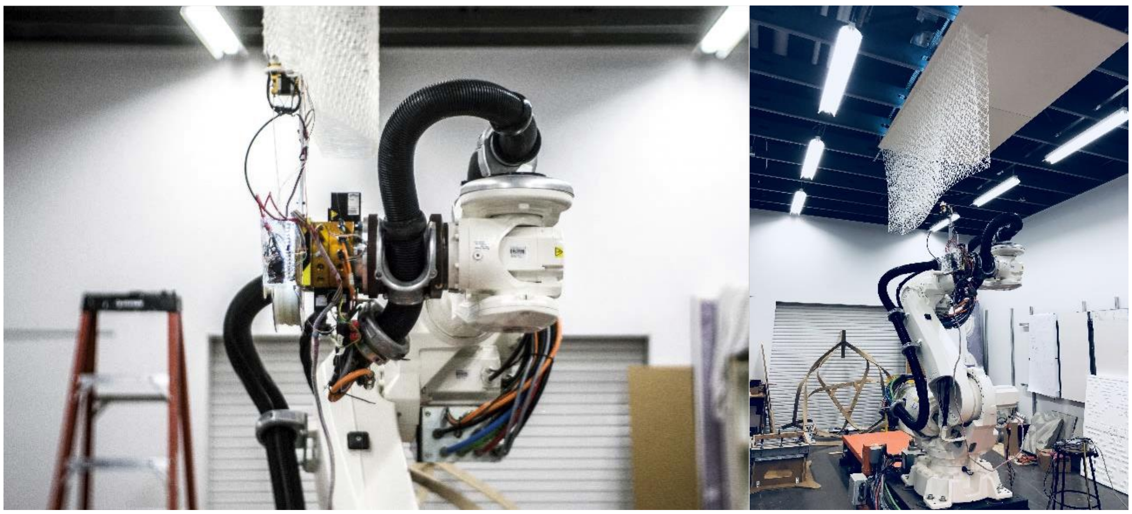


Figure 27. Mono-Resolution piece fabricated through FOAM technique

5.2.1 Geometry generation

This case studies the affordances of a continuous approach based on a "bottom up" design in which there is no given geometry discretized, but rather, a volume is built upon a 2D pattern that is repeated following a given curve. A second curve is necessary in order to determine the shape and height of the surface.

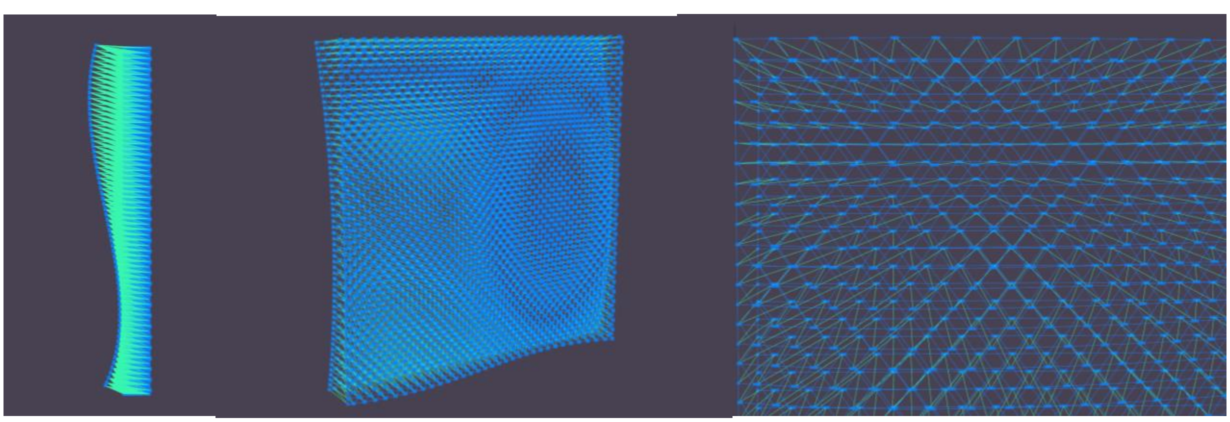


Figure 28. Case Study I generative modelling

5.2.2 Micro-scale: grammar design

To design a printable geometry, two basic rules are defined in this study case:

1. Short straight segments
2. Anchor points to stick upper layers

The taper of the straight segments needs to respect the taper of the print head, and the anchor points are converted to small horizontal segments in order to provide with a longer support for upper layers. The grammar of the pattern follows the following rule: short supporting segment – diagonal downwards segment – short supporting segment – diagonal upwards segment.

5.2.3 Meso-scale: wall design

This pattern is a 2D variation of the octedtruss pattern patented by Buckminsterfuller. This means that the same layer is repeated every two layers, woven with its upside down variation. Therefore the algorithm is designed to generate A pattern in even indexes, and B pattern in odd indexes.

This generates a self-supported lattice that conforms a uniformed surface. A secondary algorithm connects each triangle's vertex of the two main surfaces. Besides connecting both parts of the wall, provide with the necessary rigidity to make a robust wall.

5.2.4 Fabrication data

The piece was completed in a total of 40h, having a timing by layer (each layer is 2m length) as follows:

Trusses: 18 min
Continuous cord: 8 min
Weaving segments: 35 min
The speed of the robot motion was 3mm/s for trusses' segments and 7mm/s for continuous cords and weaving segments. The average wait time per node is 4s.

Figure 29. Case study I fabricated

5.3 Case Study II: Digital mono-resolution. Continuous approach. Multi-robot

This case study applies the computational method A and the fabrication workflow III. While study case I tested a novel method of fabrication, upside down, and proved that gravity was not an influential parameter at the fabrication process, case study II pretends to prove whether changing the orientation of the work object, and, therefore, the orientation of the tool, takes domination at some level of the fabrication. Also, study case II tests and analyses a synchronized behavior of two robots cooperating together, changing their orientation at different points of the manufacturing process. An ABB IRB 6640 is used for printing purposes, while an ABB IRB 4400 is programmed to hold the work object and change its orientation and location.

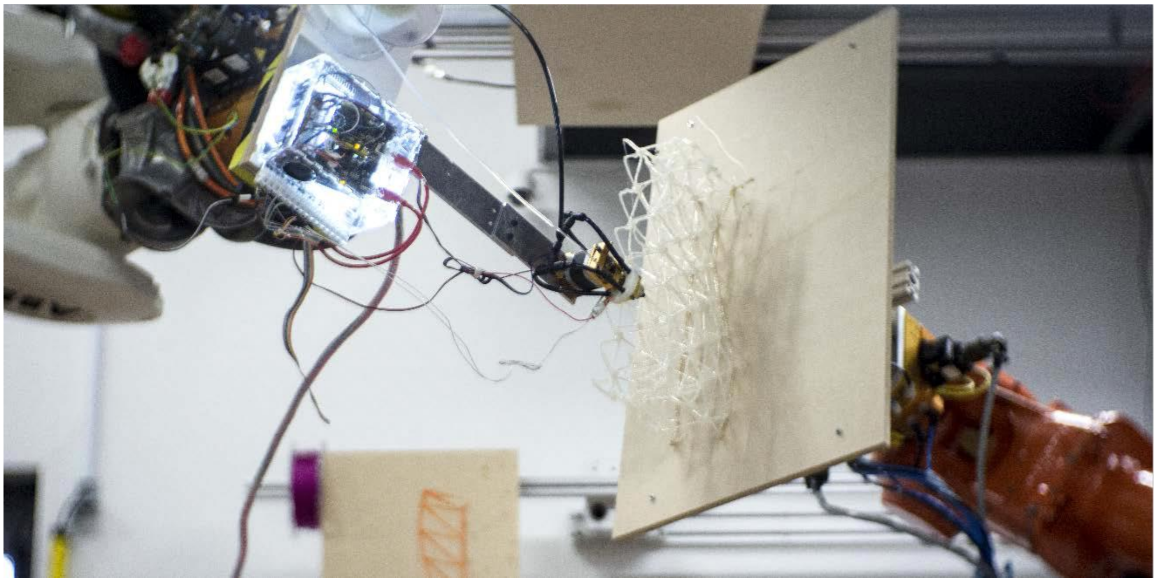


Figure 30. Case study II. Multi-robot synchronization varying 3 wObj position in real-time.

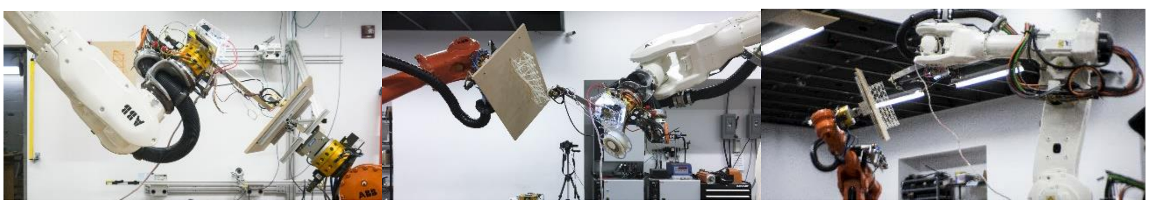


Figure 31. Work piece building process in 3 work object positions

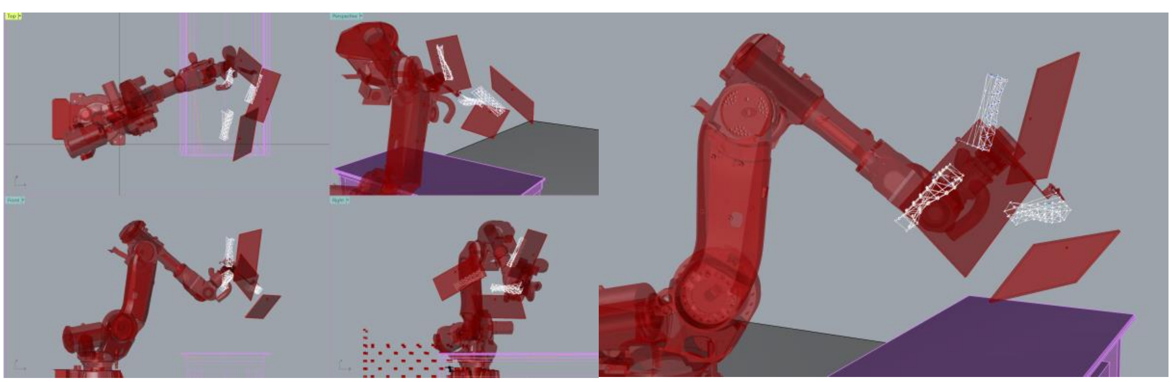


Figure 32. Wobj position digital testing

5.4 Case study III: Digital multi-resolution. Stereotomic & Continuous approach

This case study explores the computational method B and the fabrication workflow I. As described above, this design method studies the possibility of adjusting a given element to specific conditions through the application of a multi-resolution concept. Multi-resolution here is used by means of applying a higher resolution at *interesting* areas, while lowering the resolution at less *interesting* areas. While in other case studies, the flexibility of this tool presents to print onto non-horizontal work beds has been proved, in this case study, the algorithm is applied for first time, and its complexity demands an easy human-machine collaboration. A multi-material approach consisting in three different materials (PLA, PLA+ and concrete) is tested. The nomenclature consists of three patterns in a grid of 30x30x30 mm voxel size. (Figure 33)

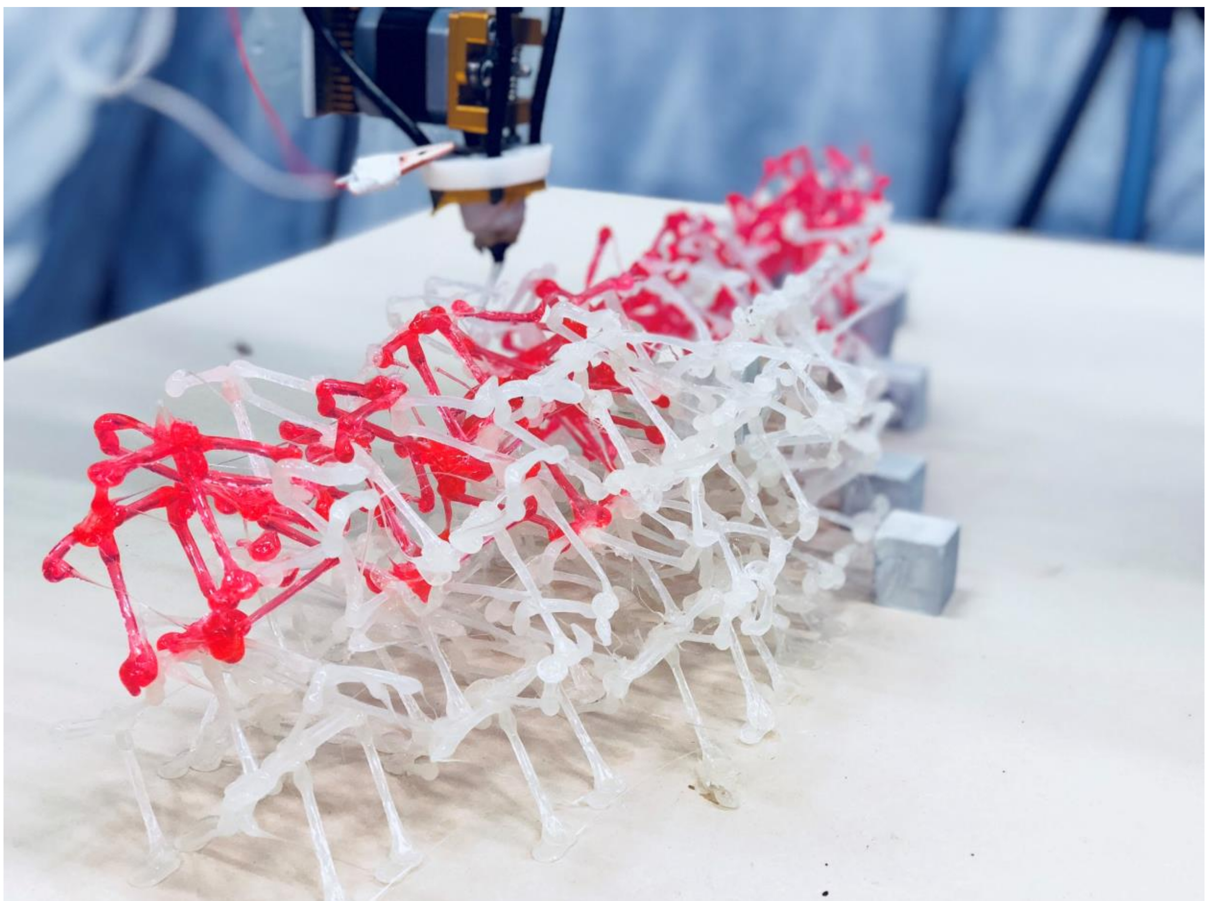


Figure 33. Multi-resolution fabrication

5.4.1 Nomenclature

A new nomenclature based on patterns that lives within the limits of a voxel is necessary in order to build a bespoke element. For the following example, a basic nomenclature of three patterns is studied and tested. Each pattern presents different conditions, such as length or material color (as a substitute for future materials). Another type of *arxel* is introduced, which consists in a concrete block, placed in those locations of the grid where the algorithm is unable to find a valid solution.

5.4.2 Redundancy

This method has redundancy as one its main features. As the design and fabrication of the tool is in an early stage that does not seeks high fidelity with complex computational processes, some imperfections happen at the end of the final segment of each *arxel.* This fact opens discussions about to what extent a high fidelity is needed in this fabrication process, and the negotiation between high/low fidelity and fabrication time.

5.4.3 Opacity variability

The multi-resolution algorithm is able to compute different opacity levels based on user inputs. It computes the length of each possible rotation of each *arxel* and searchs compares it with a list of scale of lengths, sorting the list in a way that checks whether the eligible pattern is printable. If not, the next in the list is ready to be tested, until finding a printable match. (Figure 34).

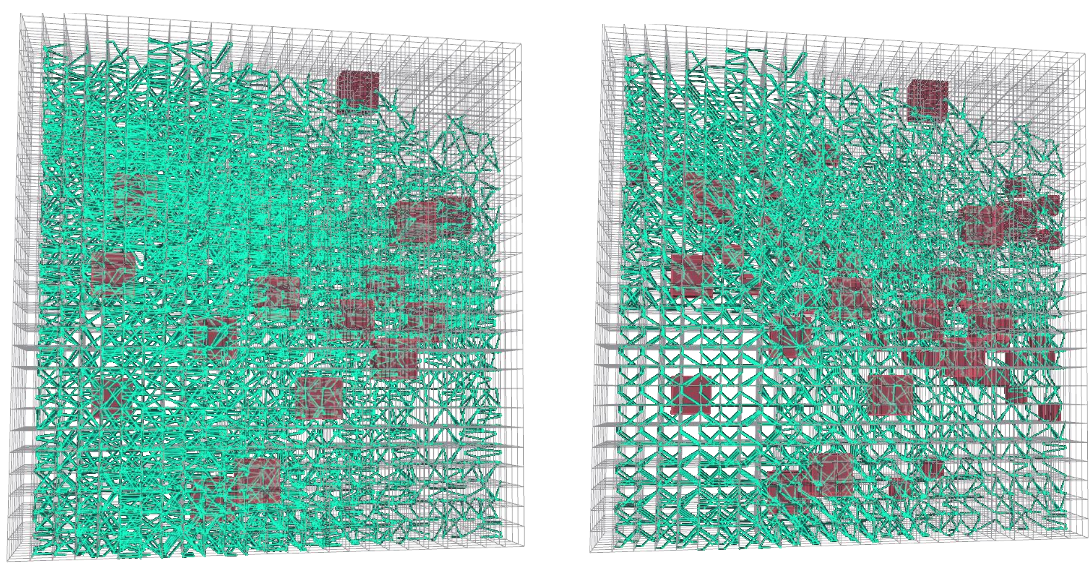


Figure 34. Opacity behaviour. More opacity (left), less opacity (right)

Figure 35. Multi-resolution multi material

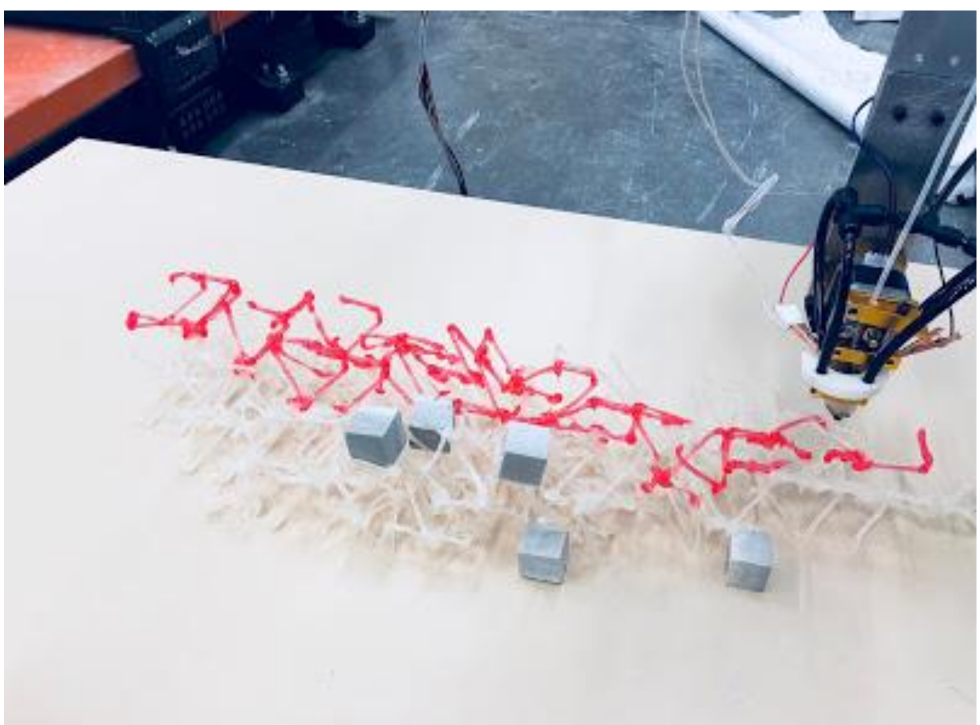


Figure 36. Multi-resolution multi material

Figure 37. Multi-resolution patterns combinatory

5.5 Case Study IV: large-scale linear extrusion

This case study explores the limitations and affordabilities of large-scale linear extrusion over different fixed existing structure, with different orientations, following the workflow II arrangement, shown at table 2. However, this part does not follow any of the computational methods explained above. Rather, it physically frames an ongoing part of the overall research that takes similar extrusion lengths (1.5 – 2.5m) as patterns for building adapted surfaces. (Figure 38).

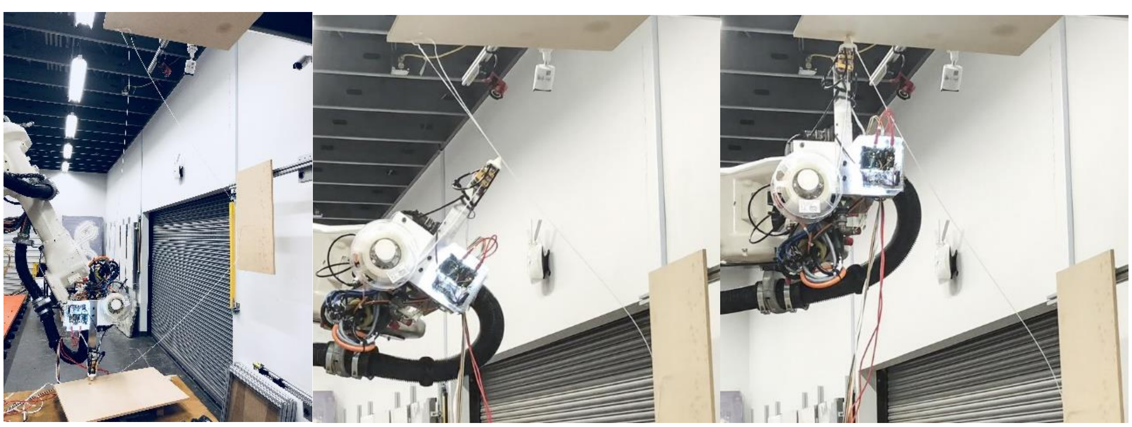


Figure 38. Case study IV. Large-scale linear extrusion

Results

This ongoing research has tested four study cases. Two important facts are studied. The first one, related to fabrication, studies novel ways of free oriented additive manufacturing over existing infrastructures. The first two study cases, prove that a horizontal ground is not needed in order to fabricate in this way. This conditions challenges the requisite that 3D spatial printing has alternatives ways of fabricating than regular 3D printers that base their printing in a layer by layer method or other spatial printing methods studied by the Bartlett School of Architecture.

The second fact is that through multi-resolutions algorithms, architects can computationally have control of every single unit of the designed space, which means that we can be technically prepared to understand architecture in a constant scale exchange. From the micro scale of the design of the pattern, to a meso and macro scale. This arises new sensibilities that we might not yet be ready to fully understand in form-spatial conditions.

The case studies gave insight about the crucial parameters to take into consideration for FOAM. The perfectible setup consists of a simple filament extrusion end effector attached to an ABB IRB 6640 robot and successfully produces large scale builds when proper tolerance parameters are implemented and work piece deformation limits are taken into consideration.

Previous studies did not explore the effects of varying nozzle orientation. Compared to existing methods for horizontal stacking, our method could adapt to more complex infrastructure conditions.

The ongoing experiments show that spatial orientation effects may be neglected if important FOAM restrictions of tolerance and work piece deformations meet.

Multi-Robot and Multi-Resolution Design Methodology algorithms prove a much larger FOAM application potential. Information embedded into the “*arxel*” unit of a Multi-Resolution system is computationally much more robust and capable of administrating efficiently architectural information.

Conclusions

In this paper, the process planning for Free Oriented Additive Manufacturing (FOAM) has been introduced.

Important steps in the process planning: computational methods for design and fabrication and the re-adjustment of the work cell to prove contrasting fabrication workflows were formulated and discussed.

Decisive strategies for fabrication have been presented by fully considering the model of Fused Deposition Modeling and Free Hanging Spatial 3d Printing. Two algorithms for geometrical configuration: mono-resolution and multi-resolution have been presented.

After that, the algorithms implemented in three case studies fabricated with FOAM technique were discussed, specifically, analyzing the results of varying nozzle extrusion directions. The stacking principle was debated and found not to be necessarily horizontal for producing functional large-scale pieces.

In summary, a negotiation between material deformation tolerances and the fidelity of the delivering technique is critical and shows great potential for significantly reducing the constraints of FOAM of complex geometries. Admitting redundancy in the fabrication process increases time efficiency.

This ongoing research will be completed by implementing more variables in a Multi-Resolution design methodology, such as structural optimizations and synchronized multi-material delivery. Also, the *arxel* unit will be studied to provide with a secondary level of intelligence, such as the ability to self-redesign its geometrical shape.

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