Design Methods for Large Scale Printing

Manuel Jimenez Garcia[1], Gilles Retsin[2]
[1,2] UCL - The Bartlett
[1] manuel.j@madmdesign.com [2] gilles.retsin@gmail.com

With an exponential increase in the possibilities of computation and computer-controlled fabrication, high density information is becoming a reality in digital design and architecture. However, construction methods and industrial fabrication processes have not yet been reshaped to accommodate the recent changes in those disciplines. Although it is possible to build up complex simulations with millions of particles, the simulation is often disconnected from the actual fabrication process. Our research proposes a bridge between both stages, where one drives the other, producing a smooth transition from design to production. The research showcased in this paper investigates tectonic systems associated with large scale 3D printing and additive manufacturing methods, inheriting both material properties and fabrication constraints at all stages from design to production. Computational models and custom design software packages are designed and developed as strategies to organise material in space in response to specific structural and logistical input. Filamentrics, the first of two projects described, intends to develop free-form space frames with robotic plastic extrusion. Through the use of custom made extruders a vast range of prototypes were developed, evolving the design process towards the fabrication of precise structures that can be materialised using additive manufacturing without the use of a layered printing method. Instead, material limitations were studied and embedded in custom algorithms that allow depositing material in the air for internal connectivity. While Filamentrics is reshaping the way we could design and build light-weight structures, the second project Microstrata aims to establish new construction methods for compression based materials. A layering 3D printing method combines both the deposition of the binder and the distribution of an interconnected network of capillaries. These capillaries are organised following structural principles, configuring a series of channels which are left empty within the mass. In a second stage aluminium is cast in this hollow space to build a continuous tension reinforcement.

Keywords: *3D printing, Robotics, Algorithm, Fabrication, Digital prototyping*

INTRO

Increased Computational Power

The exponential increase of processing power and wide accessibility of advanced fabrication equipment such as industrial robotics and 3D printers has generated a new challenge for architecture: can we increase the resolution of how buildings are designed and fabricated? Can we shift the resolution of design from bricks to particles? This paper, based on research done at the Bartlett GAD Research Cluster 4, proposes a design method to develop full architectural systems which attempts to make effective use of the increased computational power and fabrication possibilities. The research presented in this paper suggests a shift in the use of computation in architecture, from representation to a generative logic based on fabrication constraints. The design method in this paper outlines a possible approach to explore the full potential of the current state of computing and fabrication. The research agenda of RC4 investigates tectonic systems associated with large scale 3D printing and additive manufacturing methods, inheriting both material properties and fabrication constraints at all stages from design to production. Computational models and custom design software packages are designed and developed as strategies to organise material in space. SpaceWires and PixelStone use computational power to generate and simulate robotic toolpaths, which take into account structural and material constrain. (Figure 1)

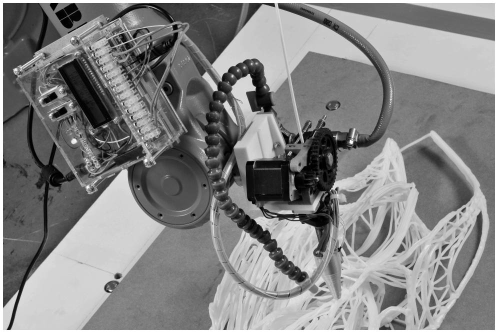


Figure 1
Robotic Fabrication - The Bartlett GAD/RC4 // Team Filamentrics: Nan Jiang, Yiwei Wang, Zheeshan Ahmed, Yichao Chen

The attempt to operate immediately on the computation of fabrication, bypasses the idea of representation. The code, the design, is effectively the instruction of construction. There is a direct connection between machine instruction, fabrication constraints, materiality, structure and the design. The rules which are driving the computational process are rules inherent to the design constraints, and are not referring to predefined modes of representation. Computational research in architecture often used algorithms inspired by natural processes to develop an architectural project. These processes were very often adopted as found objects, and imposed or projected onto the architectural project. Through developing rules which directly relate to fabrication, material and structure, SpaceWires and PixelStone develop computational methods which are inherent to architecture, and are not referential to any natural, pre-existing systems. The gap between simulation and fabrication is effectively closed.

RESEARCH CONTEXT

3D printing precedents - towards robots

The first developments of 3D printing on a large scale are associated with the research of Behrokh Khoshnevis at USC. Khosnevis developed Contour Crafting, a process which is able to organize layers of concrete on an architectural scale, effectively a large 3D printer. Another precedent is Enrico Dini's D-Shape printer, based on a process of solidifying stone dust. Both Khosnevis' and Dini's main argument is based on the idea of printing an entire building on site. A Chinese firm based in Shanghai, WinSun, commercialised a Contour-Crafting like printing process, which is able to print building elements from recycled construction waste. WinSun printed an entire, 2-story villa in Shanghai in 2015. Whereas these precedents innovated with the development of a machine, it was not their mission to develop a design methodology or speculate on the impact of their technology on architecture - the buildings WinSun produced are for example very similar to existing buildings.

On the other hand, some designers developed architectural pieces and software for existing 3D printing machines. Michael Hansmeyer and Benjamin Dillenburger developed a design software which is able to generate highly detailed architectural spaces through a process of fractal subdivision. The 3D-printed Grotto (2013), is a large-scale structure, which was designed with their software and then build in pieces on a VoxelJet machine, a German company mainly working with the car industry. Similarly, SoftKill Design developed a custom design method and software which was able to integrate structure optimisation and material distribution. The design method was tested on a prototype for a 3D printed house, which was printed as a scale-model by Materialise. Just as Hansmeyer and Dillenburger, SoftKill Design proposed to print off-site, in a factory-like environment and then ship the pieces to a site. Another precedent, Emerging Objects, a practice based in California, uses existing Zcorp printers to print panel-like pieces which are then assembled into large structures. Emerging Objects research is mainly focused on new printing materials, but not on the design method or the actual printer.

In recent years, with the increased presence of robots in academic environments, a number of people have translated FDM-like printing processes to robots. IAAC research led by Marta-Male Alemany focuses on robotic processes for clay extrusion on a large scale. Robots offer the vast advantage of increased scale, which gives architects the possibility to bypass the development of a custom, expensive machine, and immediately investigate design methods for large-scale printing. Other important precedents here are Dirk Van Der Kooijs Endless Chair, which makes use of recycled plastic extrusion, and Gramazio and Kohler's research into plastic extrusion for the use as reinforcement of concrete. As this brief overview explains, most of the efforts in large-scale architectural printing have a specific emphasis; either the machine itself, the material itself or the design itself. A more holistic setup which tackles both design logic, machine-logic and material logic has not been investigated. RC4 attempts to setup more holistic design projects engaging with large-scale printing, through using existing robot as printers. The end-goal of the large-scale printing agenda ultimately is a fabrication framework where it is quick,cheap and less energy-consuming to produce unique, highly differentiated and detailed architectural spaces.

Design Methodology: Data to Matter

The research agenda of Bartlett RC4 aims to develop integrated, holistic design methods for large-scale 3d printing, operating both at the scale of architecture, and at the level of material organisation.The design methods are tested on a 3m big physical, printed prototypes. The design methods build a generative model around logistical and fabrication constraints. The size and radius of the robot for example, constrains the maximum build-size of a printed element. Time is another important constraint, as there is only a limited availability of the robots, and they can not be moved from their position. The projects which will later be described operate with this constraints: they are printed in pieces which can be moved in and out the robot lab..Further constraints come from the material itself; initial experiments focus on how to distribute the material, and which type of nozzle is functional. The resolution of printing is defined by the nozzle and material. Other design constraints which play an important role are structural criteria - the research starts with looking at existing structural systems, such as a space-frame or dome, to then subsequently question how these systems would operate with 3D printing.

A typical 3D printing process is characterised by a layered and linear approach. This generates a number of constraints, such as for example overhangs, extrusion thickness, self-intersections, stability of material etc. Computational models aim to assign a generative agency to these constraints. The tool path not only self-organises according to the constraints but also reacts to structural analysis data. For example, the tool path attempts to distribute more material in zones with higher stress values, while at the same time also deciding locally whether it has enough support to previous layers, whether it overlaps sufficiently, or if there are no self-intersections. Recent developments work on constraints of efficiency associated with the tool path such as continuity. The less interruptions in the tool path, the quicker something can print. Optimisation techniques such as Euler Graphs and GA are used to generate efficient ways how to optimise a tool path.

The fundamental shift in this methodology, is that the loop between simulation and fabrication is closed, stripped of a degree of representation. Earlier research was often a two-stage process, where a specific form or shape was generated, which was then afterwards sliced into layers for fabrication. In this two-step process, there is no relation between the simulation and the actual fabrication or material organisation. What is computed is a representation of the object, not the physical thing itself. The research presented in this paper shifts the computational effort to computing the actual fabrication process itself. The tool path becomes a self-organizing and adaptive system, where the negotiation of different constraints generates the design.

Design Softwares: Applets
The computational process of structure optimisation, material distribution and tool path generation is synthesised in a small applet, programmed in Processing. The applet has a graphic user interface for people to interact with the complex set of constraints related to the fabrication process. The app fuses all the code necessary to generate the tool-path into one process, which is visualised as a design environment. The app allows designers to quickly generate possible versions of their work, in a more playful way, without being overly constrained by fabrication.

Tectonics
As mentioned before, the research assumes a setup where a robotic unit is positioned in a factory-like environment off-site, printing large-scale, discrete elements which are defined and constrained by the maximum bounding box of the robot. This is a deliberate choice, as the research to print on-site is more feasible if executed not with industrial robots but with distributed smaller robots. The assumption of a large-scale discrete piece generates an interesting design problem, as well as another set of logistical constraints. What is the status of this piece within a larger whole, and how can this piece be assembled into a larger whole? Computational models take this problem into account from the beginning - making it intrinsic to the research rather than as a form of post-rationalisation. The piece becomes an intrinsic part of the design, for example the gap or seam between two parts can be over-articulated or reinforced, creating both more hierarchy and more rigidity or stiffness in the boundaries of an element. These discrete, robotically printed pieces resist categorisation as a specific architectural type - it's neither wall, nor column or floor, but could act as any of these. The assembly of these proto-architectural elements generates a new type of tectonics, with a specific set of concerns which will be discussed in more detail through the case study projects in this paper.

PROJECT SHOWCASE
Filamentrics
The research project Filamentrics (Zeeshan Ahmed, Justin Yichao Chen and Nan Jiang,Yiwei Wang) looks at the possibility of 3D printing space-frame like structures to achieve a higher level of differentiation and resolution. The project makes use of robotic plastic extrusion to build space-frame like structures which are highly optimised and lightweight but at the same time ornamental and heterogeneous. (Figure 2)

The space-frame is originally developed by Alexander Graham Bell around 1900 and further explored by Konrad Wachsmann and Buckminster Fuller in the 1950s. These lightweight structures are composed of interlocking struts in a geometrical pattern which facilitates the transmission of tension and compression loads along the length of each element. The space frame counted for a long time as one of the examples of mass-produced, standardised architecture. The repetition of standardised discrete elements makes it difficult to achieve formal freedom. In recent years, a large number of more customised space-frame structures have been built, but the structure is often hidden under a cladding. For example the Heydar Aliyev centre in Baku, by Zaha Hadid Architects, get its organic and fluid appearance from a space-frame structure.

Figure 2
Rendering - Digital output from Custom Software - The Bartlett GAD/RC4 // Team Filamentrics: Nan Jiang, Yiwei Wang, Zheeshan Ahmed, Yichao Chen

Plastic extrusion or FDM (Fused deposition modelling) is type of 3d printing where ABS or PLA plastic in the form of a thin filament gets pushed through a printhead which melts it just enough so that it sticks to a previously deposited layer. FDM printers are the most common types of desktop 3D-printers, such as MakerBot and Ultimaker. To break the typically layered character of FDM prints, designers have been experimenting with these type of printing process through modifying the g-code or machine instructions for the printer. As ABS plastic cools down relatively quickly, it is possible to let material harden in the air. The Mesh-Mould project by Gramazio Kohler Research from the ETH Zurich is one of the first examples where a FDM-like printhead is fixed to a robotic arm, and material is extruded diagonally in the air to form a mesh which can be used as a reinforcement for concrete. Filamentrics focuses on a similar process of vectorial plastic extrusion with a robotic arm, further exploring the design possibilities of spatial extrusion. The main focus of this project is the computational and algorithmic organisation of material, in response to structural constraints and specific for robotic printing. Plastic is in this case only assumed as an abstract material, which could be replaced by another material in future research. A custom build plastic extrusion head was built to overcome the thickness limitations of conventional FDM 3D printers. After a series of nozzle prototypes, a final extrusion thickness of 6mm was achieved. To faster cool down the plastic, 2 adjustable tubes on the nozzle blow cold air over the extruded plastic.

Filamentrics aimed to 3D print a small pavilion using a lattice-like structure where all material is arranged according to principal lines of force, responding to different levels of tension or compression within a structure (Figure 3). According to Wolf's Law, in natural structures such as bone, material grows around principal directions of stress. A well-known precedent of this in architecture is Pier Luigi Nervi's project for the Gatti Wool Factory (Rome, 1953), which introduces a concrete slab where the beams are arranged on principal directions of stress between columns supporting the slab. The efficiency obtained by the optimisation of the structure was however compensated by the complex formwork required to achieve the high degree of differentiation.

A computational procedure was developed where agents are used to distribute robotic tool paths in response to structural data. A vector field of stress directions and levels of stress is read by an agent, which is only able to manoeuvre the field within a specific set of constraints relating to the robotic tool path. There are two types of agents active in the structure: one which distributes roughly parallel lines in relation to stress direction, and another one which builds connections in between these lines. The lattice-like structure in between lines is constrained by a specific angle under which the nozzle would intersect with the deposited material. Other constraints involves the size of a the extrusion, after some point the lattice would be too small to be printed, so then it is omitted. Experiments were tested where, just as in a gothic structure, elements bundle where higher compression values are reached, and branch out to become thinner when the stress level is lower. Each agent recognises a different level of hierarchy, modifying its behaviour to recursively generate denser zones until the structure accomplishes a sufficient level of stability.

The concept of large, discrete pieces which was introduced in the design process from the very beginning. After calculating an overall stress and load distribution for a specific space, a first generation of agents is launched, which distribute the main hierarchies of the structure. These first traces or directions are used to make decisions on how to split the structure into several parts, which are then one by one resolved into a space frame-like structure. The parts are scaled to fit within the reach of the robot used for the printing process; in this case an ABB 160. This process of generating the overall shape of the project and subsequently splitting it in parts which are subdivided into self-organizing toolpaths was developed as an application with a graphic user interface, which allowed to quickly generate toolpaths for a larger-scale project.

After a series of different experiments, a large scale pavilion-like structure of 3 x 2.5 x 2.5m was printed. This pavilion was generated piece by piece in the Filamentrics-application, in total 26 pieces were printed within one week, using one ABB 160. The pieces were assembled together by locally melting the plastic. The main constraints in this project

Figure 3
3D Printed Pavilion - The Bartlett BPro Show 2014 - GAD/RC4 // Team Filamentrics: Nan Jiang, Yiwei Wang, Zheeshan Ahmed, Yichao Chen

prove to be the speed of extrusion and the hardening of the plastic. A better cooling system and high-torque motor could speed up the printing process. The toolpath generation worked well in general, but still required a long-time of double checking in Rhino to prevent collisions and singularities with the robot itself. The constraints embedded in the code provide a basic check for intersections of the nozzle with previously printed material, but it does not incorporate a kinematics solver which can feedback the robotic constraints. A further development of this process would need to embed more of the the robotic constraints in the algorithmic process. As an architectural approach, the project did however satisfy the initial brief of the research, to develop a self-organizing toolpath which is embedded with a form of architectural agency or intend.

Microstrata

Microstrata (Maho Akita, Fame Ornruja Boonyasit, Syazwan Rusdi and Wonil Son) focuses on a compression based material to investigate a design methodology which directly bridges between simulation and additive manufacturing. The project aimed to work with powder,sand-like material which could be reinforced with a tension material at a later stage. Although the material in this case is again assumed as rather abstract placeholder - sand instead of concrete - the project aims to develop knowledge about the impact of 3D printing on reinforced concrete construction. In a later stage, with more research, the sand material could be replaced by actual cement powder, but the design methodology would remain valid.

Since the first iron reinforced concrete structure was built by François Coignet in 1853, this composite material has been in constant evolution. Today we can find a plethora of fairly different usages of reinforced concrete from post-tensioned concrete to textile reinforced concrete. Despite the introduction of prefabricated reinforcement or advanced digital processes which guarantee the optimum placement of steel members, the bottleneck for streamlining the construction process is the labour-intensive placement of rebar and formwork. Microstrata looks at large scale additive manufacture of reinforced concrete in powder-form, with tension material cast in printed cavities rather than using rebar. A computational process is developed which is able to organize a continuous network of channels on directions of principal stress, inside a concrete mass acting in compression. Previously mentioned precedents of printing concrete, such as Khosnevis and WinSun, are constrained by the use of rebar, which has to be added afterwards.

The fabrication process developed by Microstrata is inspired by Powder-bed 3D printing, which can be found in machines such as Z-Corp powder printers or SLS printers. First developed by Massachusetts Institute of Technology in 1993, this process has been widely used in the last decade. The powder in the bed is used as a supporting material for the next layers of printing, which makes the process significantly easier than FDM-based printing, which inevitably encounters problems with overhangs and cantilevers. The largest scale powder printers are the ones developed by VoxelJet and ExOne, which are mainly used to print sand-cast moulds for the car industry. Nonetheless, scale limitations have not allowed architecture to adopt this process more intensively. The use of sand based material reduces dramatically the price of large scale objects, allowing it to be used at an architectural scale.

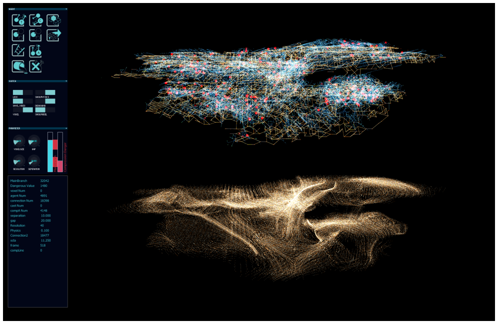
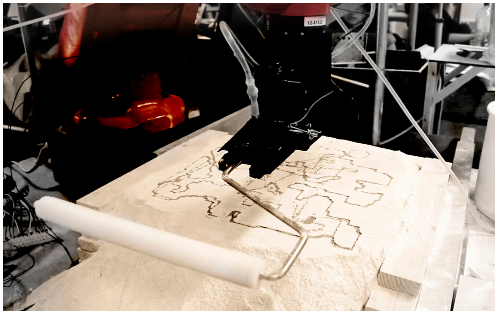


Figure 4
Custom Software Screenshot - The Bartlett GAD/RC4 // Team Microstrata: Wonil Son, FaFame Boonyasit, Maho Akita & Syazwan Rusdi



Microstrata created a custom powder bed 3D printer using a small ABB 120 robot, and a custom build nozzle. The nozzle consists of a needle with a valve to drop precise amounts of binder, as well as a roller to flatten the sand surface before binding. One drop of binder can be understood as a voxel of matter, a 3-dimensional pixel. Microstrata's computational workflow therefore focuses on voxels rather than the more linear approach from Filamentrics. Every voxel, or drop of binder becomes a unit of computation.

An application was developed which evolves through a number of stages. In the first stage, a model of stress distribution is imported as a vector field. An agent-based system is launched which organises a network of tension on the stress map. The trajectories are connected to each other with bracing lines. To allow for casting, a second agent organised air channels from the tension network. Compression material is translated as continuous lines around the principal compression stress line (Figure 4).

Subsequently, in a second stage, this network is translated to a voxel-based setup which corresponds to the fabrication method. To build a channel with minimum thickness of one voxel, a total of 8 voxels is required to be bound together. Cellular-automata rules were developed to translate the abstract network into voxels, preventing for example intersections of channels. The compression network is developed in response to the amount of stress, which translates some trajectories as thin, fibrous strands and others as thick, solid zones of multiple layers of voxels. From this process emerges a porous block of material with a continuous network of capillary channels for tension material.

The ABB robot follows a uniform, preset trajectory for every layer, with the nozzle valve just opening or closing if a voxel needs to be materialised or not. Given the basic and low-tech nozzle, the printing resolution of this system is remarkably accurate, with voxels measuring 4mm (Figure 5). The main challenges for this printing process turned out to be the optimisation for the channels to work with the demanding constraints of an actual casting process such as of aluminium. Some experiments were done at a local foundry to cast aluminium inside of the channels - but this prove to be very difficult. Some channels blocked quickly, and the resulting structure was not as continuous as it should be (Figure 7). In further stages of research, it would be interesting to use hydrated cement instead of sand powder, which would improve the strength of the structure. Unlike Filamentrics, Microstrata did have problems connecting multiple elements together, the connection was not considered enough in advance and made precise connections difficult.

Figure 5
Robotic Fabrication - GAD/RC4 // Team Microstrata: Wonil Son, FaFame Boonyasit, Maho Akita & Syazwan Rusdi

Figure 6
3D Printed Sandstone physical prototype - The Bartlett BPro Show 2014 - GAD/RC4 // Team Microstrata: Wonil Son, FaFame Boonyasit, Maho Akita & Syazwan Rusdi

Figure 7
The Bartlett BPro Show 2014 - GAD/RC4

CONCLUSION:

Filamentrics and MicroStrata illustrate the importance of integrating algorithmic processes of material organisation in the research on large-scale 3D printing. The projects manage to narrow the gap between simulation and fabrication through incorporating constraints as generative elements in the design process. In both projects, there is a tight relationship between fabrication constraints, materiality, computation and the final design outcome. The gap between design and fabrication can be narrowed through the use of computation which operates as a system to organise material in response to specific concerns of structure, fabrication and design.

Different material principles result necessarily in different structural systems, which in turn require their own machinic processes and algorithmic logic. The specific material constraints of a compression-based project like Microstrata requires a computational process which is more concerned with the precise organisation of pixels of matter. Filamentrics, focusing on a space frame-like structure, requires a computation and fabrication method which articulates the direction of stress.

In order to successfully scale up 3D printing processes, an approach is required which can work across scales, from the large-scale of the building, to the scale of the material and tool path. The interaction between these different scales enables the full potential of 3D printing large-scale architectural elements to be realised, and gives rise to new types of spaces with a previously unseen level of detail, which can be created faster and cheaper than with traditional building construction methods.

CREDITS

- Bartlett GAD-RC4 Studio Masters: Manuel Jimenez Garcia & Gilles Retsin
- Technical Support: Vicente Soler & Thibault Schwartz
- Team Filamentrics: Nan Jiang, Yiwei Wang, Zeeshan Ahmed & Yichao Chen
- Team Microstrata: Wonil Son, Fame Boonyasit, Maho Akita & Syazwan Rusdi
- Bartlett GAD Director: Alisa Andrasek
- The Bartlett B-Pro Director: Professor Frédéric Migayrou, B-Pro Director
- Main Softwares and Libraries used: Processing by Casey Reas and Ben Fry, Toxiclibs library by Karsten Schmidt, McNeel Rhinoceros + Grasshopper, HAL by Thibault Schwartz, Autodesk Maya, Autodesk 3Ds Max, Pixologic ZBrush

REFERENCES

Bandel, H 2001, *Structure Systems/Tragsysteme*, Hatje Cantz

Bryant, LR 2011, *The Democracy of Objects*, MPublishing, University of Michigan Library

Kohler, M 2014, *The Robotic Touch*, Park Books

Nervi, PL 1965, *Aesthetics and Technology in Building*, Harvard University Press

Spuybroek, L 2011, *The Sympathy of Things: Ruskin and the Ecology of Design*, V2_Publishing