3D printed chairs – RC4 204-15 // Team CurVoxels: Hyunchul Kwon, Amreen Kaleel and Xiaolin Li4.1 CurVoxels

FROM CONTINUOS TO DISCRETE FABRICATION

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1. Mind the gap

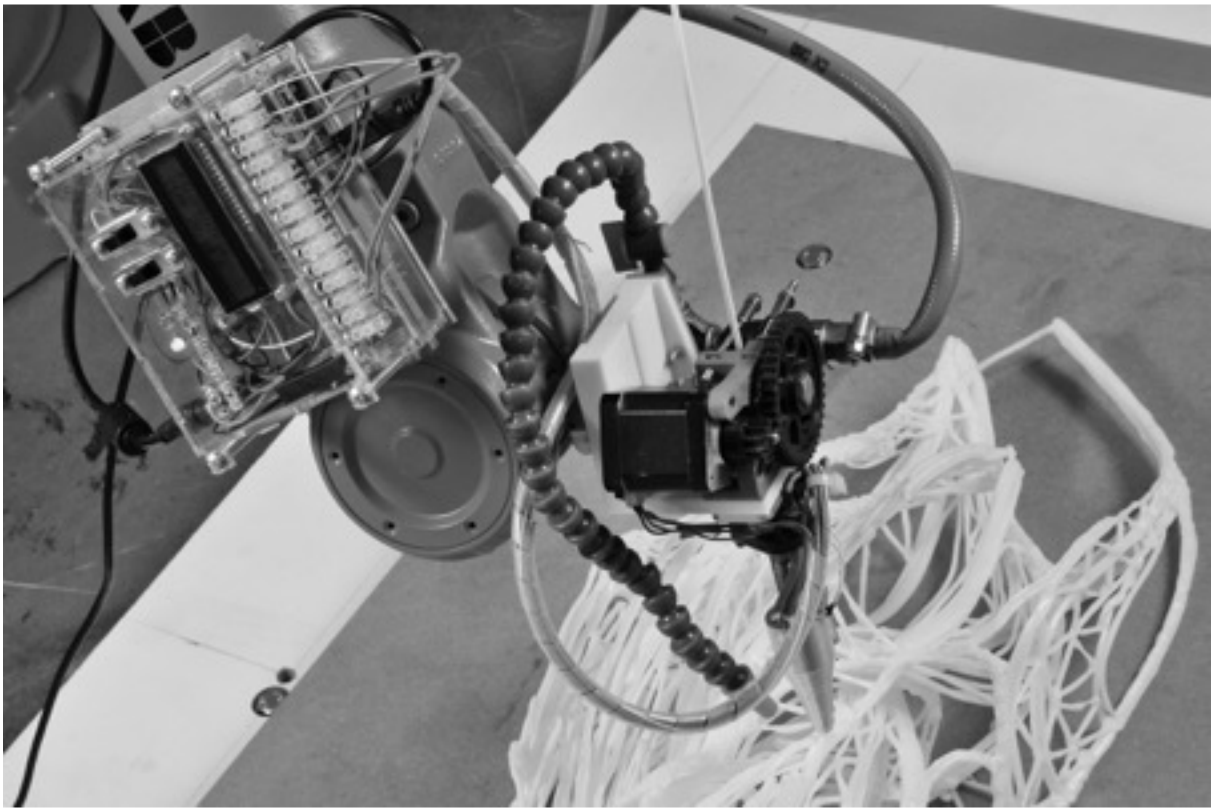
With an exponential increase in the possibilities of computation and computer-controlled fabrication, the idea of an architecture of extreme detail and resolution becomes feasible. This possibility has been extensively explored by designers such as Benjamin Dillenburger and Michael Hansmeyer. It became one of the conceptual drivers in the work of practices such as Biothing and TheVeryMany. SoftKill's Protohouse project (2012) is also an early exploration of an architecture with extreme detail. The advantages of increasing the resolution of architecture are manifold. According to Dillenburger and Hansmeyer "3D printing introduces a paradigm shift in architecture, where the amount of information and complexity of the output is no longer a relevant constraint" (Dillenburger B, Hansmeyer M, 2013). Architecture can start to respond in a very precise way to structural criteria or external forces and demands. An increased level of detail also offers new opportunities for aesthetic exploration.

The increase in computational power, availability of industrial robots in academia and distribution of programming knowledge has accelerated computational design research in the past few years. Mass Open Online Classes (MOOC) and other initiatives such as the Plethora Project have made it relatively easy for generations of students and researchers to pick up even more complex code. Research in advanced fabrication has increasingly become more accessible.

However, although it is now feasible to build up complex simulations with millions of particles, the resultant simulations are often disconnected from the actual fabrication process. There is a gap between the digital design process and the fabrication method. This paper will further argue that this gap exists as a result of a misalignment between the machine and the design process. Often, simulation doesn't take fabrication into account and designers or researchers prefer to post-rationalise the resultant forms. The possibility of a more holistic approach, where a designer is in control of both the computational design process and the fabrication is an evolution which has only become feasible in recent years with the proliferation of new robotic technologies and digital knowledge.

Mario Carpo divides the past 20 years of digitally intelligent architecture into a first and second digital age. The first digital age, with people like Greg Lynn, Bernard Cache and Zaha Hadid; is interested in the idea of continuity. Architecture is understood as a continuously evolving body - a kind of embryo developing under the pressure of an external field of forces. To become reality, the organic, continuous forms of the first digital age had to be subdivided into CNC-milled panels and frames. The first digital age remained a "paper architecture" as it had no intrinsic link with concepts of fabrication. In contrast, the second digital age understands computational processes as fundamentally discrete. EZCT explored this idea of discreteness through their design of a voxel-based chair. However, just as in the first digital age, this second digital age of "big data" is in intrinsic trouble with tectonics and materialization. To materialize the second digital age's discrete explorations, continuous fabrication techniques are required: cnc-milling molds or 3D printing. This causes a misalignment between the computational method, which is able to negotiate millions of particles, and the hermetic constraints of these continuous fabrication processes. To translate the complex structures generated in the simulation, data often has to be reduced to a series of slices, contours or layered toolpaths. The translation to physical form reduces the complexity of the structures, effectively removing information. Since the actual organisation of material has not been computed in the simulation, it remains a post-rationalised process.The work presented in this paper attempts to negotiate this gap, by introducing machine constraints as generative drivers of the computational process. The research attempts to establish a one to one relationship between the organisation of digital and physical data.

This paper will describe in detail how this gap can be negotiated within a fabrication framework based on continuous 3D printing. The first iteration of projects described uses continuous computational systems to integrate fabrication constraints within the design method. The second iteration of this research attempts to utilise discrete computational models. As a brief introduction, a third iteration will be introduced, which proposes discrete methods for both computation and fabrication.



Robotic printing - The Bartlett RC4 2013-14 // Team Filamentrics: Nan Jiang, Yiwei Wang, Zheeshan Ahmed, Yichao Chen

2. Towards large scale additive manufacturing

The projects described in this paper are produced in a research through teaching context at Research Cluster 4 (RC4) in UCL the Bartlett school of Architecture. RC4 is a part of B.PRO, an umbrella of post-graduate programs in architecture at the Bartlett. The cluster is lead by Gilles Retsin and Manuel Jiménez García, and started out in 2013. Since the start of the cluster, there has been a close collaboration with Vicente Soler. From the early stages, the research agenda of RC4 has focused on large scale additive manufacturing for architecture. The research makes use of industrial robots, which are turned into 3D printers by attaching custom designed end-effectors for additive manufacturing. This effectively turns industrial robots into large format 3D printers. RC 4 is part of a larger body of research in large scale printing. Large scale 3D printing for architecture is often associated with Behrokh Khoshnevis' Contour Crafting procedure. Contour Crafting enables the printing of large scale concrete structures from a gantry structure. A similar process developed by WinSun in Shanghai has entered the commercial market, producing a large number of full scale prototypes in the past few years. Enrico Dini's D-Shape printer is also based on a large gentry, but it uses a binder to solidify stone dust into a sandstone-like material. While these precedents successfully innovative with the development of a machine, they are not innovative with the design methodology itself. They are effectively investigating only one side of the gap - the fabrication process. On the other hand, the research by Dillenburger and Hansmeyer is specifically focused only on design, and not on fabrication. They assume the existence of a large scale 3d printer, using a commercially available printer such as the Voxeljet sand printers.

There are a number of important precedents using robots as 3D printers. By using a robot, researchers can skip the expensive and slow process of developing a new, large scale machine from scratch. IAAC research led by Marta-Male Alemany was the first to focus on robotic processes for additive manufacturing in an architectural context. Gramazio and Kohler's research at the Future Cities Laboratory in Singapore was the first to introduce spatial plastic extrusion with a robot arm. Outside of architecture, the aerospace industry has been investigating metal sintering processes with robots.

Research in RC4 starts out with the choice of a specific material and printing process. Students start the research by exploring material properties. For instance, in the case of concrete or plastic, the material is tested for consistency of extrusion, through a series of manual tests. As a second step, students develop a custom-built extruder. This extruder is then first manually tested, and later on mounted on a robot. Multiple iterations of the tool head are developed. Over the past two years RC4 developed more than seven iterations of a plastic filament extruder, gradually increasing speed and precision. The designs of this extruder are available for a next generation of students to further develop. The tool is always intrinsically linked with a chosen material for printing. RC4 has developed tools for robotic 3D printing in clay, plastic, sand, concrete and timber.

Students synthesize the computational process for tool path generation in a small applet, programmed in Processing. The applet has a graphic interface for users to interact with the complex set of constraints related to the fabrication process. The applet fuses all the code necessary to generate the tool-path into one single process, which is visualised as a design environment. It allows designers to quickly generate possible versions of their work, in a more playful way, without being overly constrained by fabrication. RC4 research advocates the idea that architecture should develop its own algorithmic methodologies, based on constraints from the fabrication process, rather than borrowing methods from natural systems. Most of the algorithms underlying the work of the second digital age (Carpo, 2012), such as recursive subdivision, fractal growth, cell-division, agents or reaction-diffusion are driven by observations into natural systems. The algorithms can be considered "found objects", which don't take into account constraints relating to materialization, structure or constructability.

Applet Screenshot - The Bartlett RC4 2013-14 // Team Filamentrics: Nan Jiang, Yiwei Wang, Zheeshan Ahmed, Yichao Chen

This paper will discuss a gradual shift from continuous to discrete computation using four projects, spread over two years of research. Filamentrics and CurVoxels, which are based on lightweight plastics; and Microstrata and Amalgama, which are based on compression materials such as concrete. The first two projects take on board the idea of spatial extrusion of plastics, rather than printing in layers. Filamentrics is based on a continuous computational method which uses an agent-based algorithm to develop toolpaths in space, in response to a field of forces and specific ideas of structure. CurVoxels uses the same fabrication technique of spatial printing, but changes the computational method to a discrete method based on voxels. While these two projects investigate lightweight, space-frame like structures which mainly operate in tension, the next two projects are based on heavy, wet processes utilising compression-based materials. Microstrata developed a D-Shape like process of powder printing, where sand is solidified with a binder, resulting in heavy, strong, sandstone-like blocks. The next iteration of that project, Amalgama, replaces the sand for actual concrete. A powder based support bed is used to support layers of extruded concrete, allowing for more formal freedom, such as large cantilevers.

3. Continuous Computation

3.1 Filamentrics

Filamentrics (Zeeshan Ahmed, Nan Jiang, Justin Yichao Chen, and Yiwei Wang) investigated spatial 3D printing of space-frame like structures with a high degree of differentiation. The project is based on a 3D version of a classic FDM (Fused Deposition Modelling) process. Instead of printing in layers, hot plastic is extruded along a vector and cooled down with cold air to solidify quickly in space. There has been a number of precedents for these kind of processes, mainly with small scale 3D printers. The G-Code or machine input is modified by the designer to work in three dimensions. This process was first brought to a robot for the project Mesh-Mould, by Gramazio Kohler at the ETH/Future Cities Lab in Singapore in 2012. An FDM-like extruder is attached to a robotic arm, and used to extrude a mesh-like structure which is then used as a formwork for a semi-liquid kind of concrete.

Rendering - The Bartlett RC4 2013-14 // Team Filamentrics: Nan Jiang, Yiwei Wang, Zheeshan Ahmed, Yichao Chen

Filamentrics aims to 3D-print heterogeneous space-frame like structures, where material is organised according to principal lines of stress. The material organisation also responds to other types of structural data such as the amount of stress. To achieve this heterogeneity and adaptability to structure-data, an agent-based system was used. Principal lines of stress are translated as a vector field, which can be implemented and read by a series of agents. While manoeuvring the vector-field, the agent creates a toolpath trajectory for the robot. The agent gets a series of constraints which relate to the constraints of the fabrication process. For example, it's prevented to self-intersect with existing lines. A minimum and maximum distance between trajectories is also constrained. In a subsequent stage, a second set of agents connects the previously generated lines together. These triangular connections are again subjected to a series of constraints. The lattice-like structure in between lines is constrained by a specific angle under which the nozzle would intersect with the deposited material.

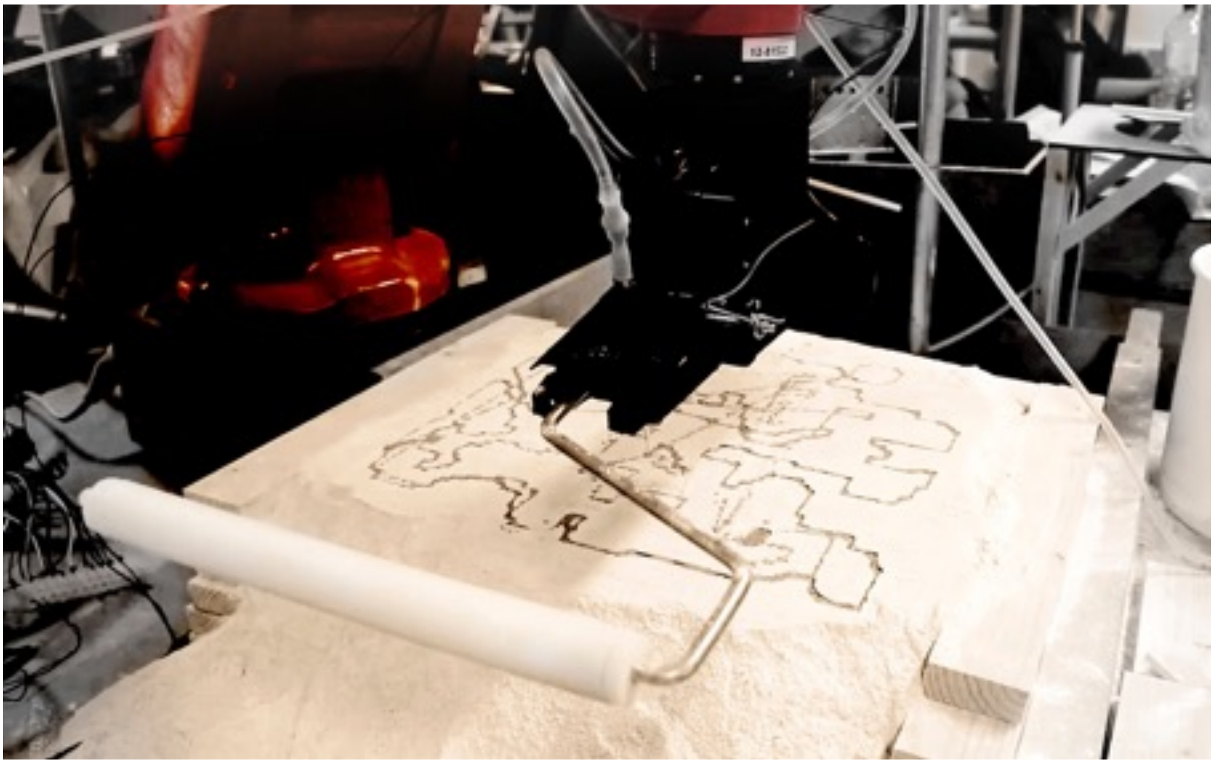
The organisation of these trajectories responds to the amount of stress through bundling: where there is a high level of stress, lines start to cluster together. The designed structures are initially generated as a whole, but can then be broken down into designed pieces which fit the maximum workspace of the robot. This process of generation is entirely scripted in a Processing-based applet. Once the structure is generated, it's exported as a text-file to Rhinoceros/Grasshopper. HAL is used to generate the actual machine code to drive the robot, and communicate with the extruder. As a final output, a 3 x 2.5 x 2.5m pavillion was printed. It consisted of 26 pieces generated by the applet developed for the project.

Physical prototype - The Bartlett RC4 2013-14 // Team Filamentrics: Nan Jiang, Yiwei Wang, Zheeshan Ahmed, Yichao Chen

The generative process takes a number of constraints into account, but the resultant structures still need a large amount of time to solve errors, intersections and singularities. Due to the heterogeneity and large amount of variation in the generated toolpaths, it's difficult to automate the post-rationalisation. Problems and errors are, just like the structure itself, continuously different and require unique solutions. This means that the file preparation becomes time-inefficient. The nature of this problem lies in the continuous character of the generative process. Errors can't be serially solved, and large amounts of time or computational power is needed to prevent them from occurring. The continuous nature and interdependency of the agent-trajectories also fundamentally doesn't allow for a local problem solving. If a problem occurs, the whole system has to be rerun to solve it.

3.2 MicroStrata

Microstrata (Maho Akita, Fame Ornruja Boonyasit, Syazwan Rusdi and Wonil Son) uses the opposite kind of materials as Filamentrics: heavy, compression based sandstone. The project is based on a powder-printing process, similar to Enrico Dini's D-shape. A layer of sand is spread out and flattened by a custom made end-effector on the robot. The nozzle itself consists of a needle connected to a valve, which drops binder. The custom-developed software for this research project understands every drop of binder as computable matter. The team adopted an approach based on voxels or three-dimensional pixels, in combination with an agent-based system. In a similar way as Filamentrics, agents are used to distribute and organise a network of connections. In this case two different types of agents are developed, one which reacts to tension and one to compression. This network is then effectively voxelised. Voxels containing compression data trigger the end-effector to deposit binder, whereas tension areas remain empty. The data generated by the processing applet is effectively just a voxel containing a boolean statement to open or close the nozzle valve. At a later stage, aluminium is cast inside the cavities left by the tension network.



Robotic Fabrication – RC4 203-14 // Team Microstrata: Wonil Son, FaFame Boonyasit, Maho Akita & Syazwan Rusdi

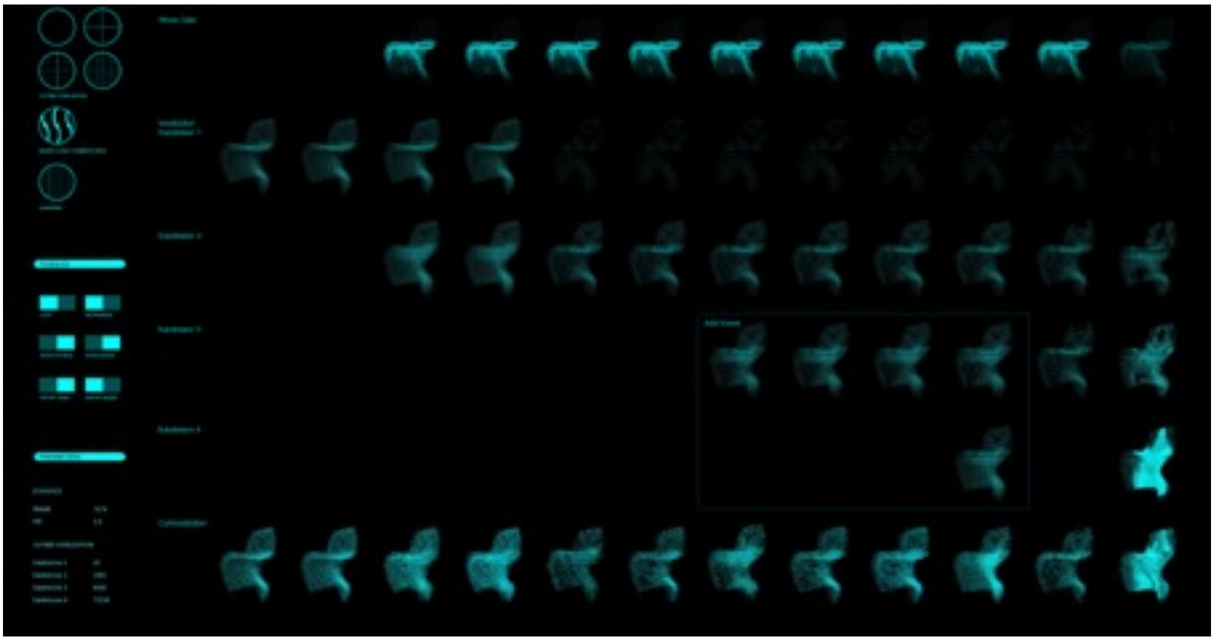
To give an example, for building an enclosed tension channel, 8 voxels need to be bound together. The size of one voxel or drop of binder is 4 x 4mm. To achieve these types of precise typologies, a Cellular Automata logic is developed, which can expand the initial voxel and form channels or bridges. The compression network develops as solid zones, reacting to amounts of stress. In areas with high stress levels, a thicker cluster of voxels is generated. This process resulted in a series of porous sandstone structures, connected with a capillary network for tension material.

Compared to Filamentrics, Microstrata employed a less linear and continuous fabrication process. Although the material distribution is continuous, the voxel and CA logics introduce a degree of discreteness in the process. The process of preparing robotic control data in Grasshopper proved to be simpler. The CA logics were relatively efficient at problem solving.

Physical prototype – RC4 203-14 // Team Microstrata: Wonil Son, FaFame Boonyasit, Maho Akita & Syazwan Rusdi

4 Discrete Computation

Taking on board the problems associated with continuous, generative processes, the second iteration of research, conducted during the academic year 2014-2015, focused fundamentally on discrete computational processes.



Applet Screenshot – RC4 204-15 // Team CurVoxels: Hyunchul Kwon, Amreen Kaleel and Xiaolin Li4.1 CurVoxels

CurVoxels (Hyunchul Kwon, Amreen Kaleel and Xiaolin Li) continued the spatial printing research from Filamentrics, but focused on a voxel-based combinatorial logic to generate the toolpath. The team continued the development of the plastic extruder initiated by Filamentrics, adding higher torque motors and a better cooling system. A combinatorics algorithm is used to aggregate a single curvilinear element into a continuous, kilometres-long extrusion, which allows for an uninterrupted printing process .

3D printed chairs – RC4 204-15 // Team CurVoxels: Hyunchul Kwon, Amreen Kaleel and Xiaolin Li4.1 CurVoxels

An initial shape is voxelized, taking structural forces as a driver for the distribution of voxels. The size of the voxels changes in response to the amount of stress, distributing different material densities. When voxels are very small, the embedded spatial curve effectively becomes no more than a line. What appears to be two different formal syntaxes, curvilinear versus linear, is actually the product of a single spatial curve on different scales. The system works by calculating tangents and points of connectivity to other voxels from the curve of a single voxel. Each discrete voxel unit has 24 possible rotations, which enables it to generate a differentiated, heterogeneous pattern. Converting a curve into a discrete voxel unit enables quick evaluation of printability with a high level of control over patterns.

The fundamental advantage of this serial approach is that a toolpath only has to be optimised and tested for one voxel, in 24 different rotations. Afterwards, thousands of these voxels can be aggregated, but the connection problems remain finite and manageable.

4.2 Amalgama

Amalgama (Fran Camilleri, Nadia Doukhi, Alvaro Lopez Rodriguez and Roman Strukov) develop a project based on the agenda of printing compression based structures. In this case, the fabrication method combines two already existing concrete 3D printing methods: extrusion and printing.This combination of techniques has given rise to a form of supported extrusion. Concrete is extruded layer by layer over a bed of granular support material. Due to the support, the resulting extruded concrete is of a much higher resolution, and large cantilevers are achievable. The supported extrusion method developed by Amalgamma gives designers more formal freedom and less constraints, while introducing more variation in, what is traditionally,a layered concrete extrusion processes.

Robotic Concrete 3D printing – RC4 204-15 // Team Amalgama: Francesca Camilleri, Nadia Doukhi, Alvaro Lopez Rodriguez and Roman Strukov

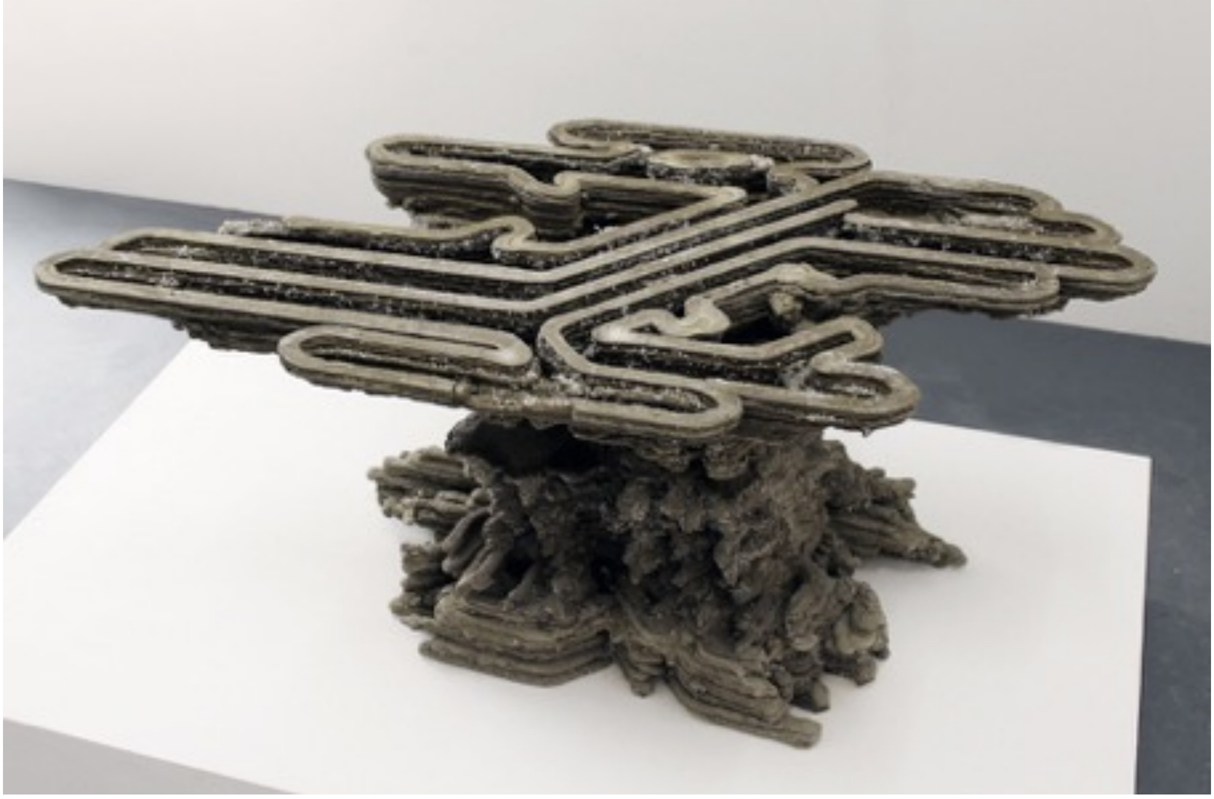
The team also developed a combinatorics-based code, where every voxel has a specific type of pattern inscribed on its face. The voxels rotate into a position which establishes a continuous pattern. In a second stage, this two dimensional pattern is grown into a three dimensional volume with a smaller kind of voxel. In a last iteration, these small scale voxels are assigned a discrete part of the toolpath with a random start position. These discrete pieces of toolpath are then connected into the longest continuous line possible, within one layer of the structure.

5 Next Steps

RC 4 engaged for a cycle of two years with the idea of 3D printing large scale structures. The third iteration, which is ongoing, investigates the advantages of shifting to a discrete fabrication method, rather than a continuous one. 3D printing can be considered a continuous method, as it continuously glues or melts particles together, with an infinite connection scheme. Continuous fabrication processes have intrinsic problems with fundamental issues such as speed, structural performance, multi-materiality and reversibility. Discrete or "digital" fabrication processes are based on a small number of different parts, having only a limited number of options for connecting together . The design possibility, or the way how elements can combine and aggregate is defined by the geometry of the element itself - which leads to a "tool-less" assembly. The geometry of the parts being assembled provides the dimensional constraints required to precisely achieve complex forms.

Aligning discrete computation with discrete fabrication, enables the designer to bridge the gap between the digital and the physical. Digital Data is the same as physical data. The physical organisation of matter becomes "digital", in the sense that it maintains its discreteness and the potential to be re-assembled.

Discrete fabrication has the same type of advantages in terms of problem-solving as discrete computation: problems are serialised and solutions therefore become repeatable and cheap. The fundamental problem of 3D printing lies in multi-materiality: a process of voxel-assembly can deposit infinite variations of material. Rather than using robots as 3D printers, this next phase of research uses robots as voxel-assemblers or voxel-printers. robots quickly pick and place discrete bits of matter, assembling it into heterogeneous aggregations.



3D printed concrete Table – RC4 204-15 // Team Amalgama: Francesca Camilleri, Nadia Doukhi, Alvaro Lopez Rodriguez and Roman Strukov

6. From continuous to discrete

The research in the first year or RC4 research started out with design methodologies based on continuous computational systems such as agent-based algorithms. These were used to simulate the deposition and organisation of material in space, a process which is then translated to the robot. This workflow led to a few observations: the translation from a continuous system to a set of toolpaths for the robot is often very time consuming and still needs post-rationalisation. The continuous systems become increasingly computationally expensive. To incorporate all the constraints from the printing process in a continuous toolpath requires heavy computing and a large amount of memory.

These observations have led to a shift towards discrete computational methods in the second year of the research, focusing on computing discrete parts of the toolpaths. These are first generated in one voxel, where all the constraints are optimised and tested. In a second stage, a large number of voxels are combined together into one continuous path. This method only requires local computation, and is as such computationally inexpensive and quick. The prototyping aspect also becomes much quicker, as only one voxel has to be checked for problems. Rather than continuous differentiation, heterogeneous structures were achieved by always rotating the piece of toolpath contained in the voxel into different positions. These discrete approaches prove to be successful. The serialisation of the discrete toolpath patterns means that there is a reduction of unique problems to solve. One fragment of the toolpath can be optimised, and then serially repeated and combined into a larger toolpath. Continuously generated toolpaths have a complicated and large amount of unique connection problems, each of them requiring a different solution to become a printable structure.

To overcome the risk of generating rather homogenous structures due to the serial repetition of voxels, the idea of combinatorics was used. Through always rotating the discrete element in different positions, highly heterogeneous and differentiated structures became feasible. This is a fundamental shift in digital design thinking: from mass-customization and continuous differentiation, to discrete, serially repeated systems which can still maintain a high degree of heterogeneity. This approach not only brings the feasibility of printing digitally intelligent structures a step closer to reality, but also makes 3D printing more accessible. As problems are serialised and easy to solve, there is no need for expensive problem solving equipment such as advanced sensors, camera trackers or supercomputers.

3D printed staircase – RC4 204-15 // Team CurVoxels: Hyunchul Kwon, Amreen Kaleel and Xiaolin Li4.1 CurVoxels

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