Robotic Spatial Printing

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There has been significant research into large-scale 3D printing processes with industrial robots. These were initially used to extrude in a layered manner. In recent years, research has aimed to make use of six degrees of freedom instead of three. These so called ``spatial extrusion'' methods are based on a toolhead, mounted on a robot arm, that extrudes a material along a non horizontal spatial vector. This method is more time efficient but up to now has suffered from a number of limiting geometrical and structural constraints. This limited the formal possibilities to highly repetitive truss-like patterns. This paper presents a generalised approach to spatial extrusion based on the notion of discreteness. It explores how discrete computational design methods offer increased control over the organisation of toolpaths, without compromising design intent while maintaining structural integrity. The research argues that, compared to continuous methods, discrete methods are easier to prototype, compute and manufacture. A discrete approach to spatial printing uses a single toolpath fragment as basic unit for computation. This paper will describe a method based on a voxel space. The voxel contains geometrical information, toolpath fragments, that is subsequently assembled into a continuous, kilometers long path. The path can be designed in response to different criteria, such as structural performance, material behaviour or aesthetics. This approach is similar to the design of meta-materials - synthetic composite materials with a programmed performance that is not found in natural materials. Formal differentiation and structural performance is achieved, not through continuous variation, but through the recombination of discrete toolpath fragments. Combining voxel-based modelling with notions of meta-materials and discrete design opens this domain to large-scale 3D printing. Please write your abstract here by clicking this paragraph.

Keywords: *discrete, architecture, robotic fabrication, large scale printing, software, plastic extrusion*

INTRODUCTION

The research presented in this paper is produced at the Design Computation Lab, University College of London (UCL), and led by Manuel Jimenez Garcia, Gilles Retsin and Vicente Soler. Since 2013, one of the labs research strands has been the development of design methods for additive manufacturing with robots. The term spatial extrusion (Mesh Mould, 2008) refers to a manufacturing technique in which plastic is mostly extruded in the air without any support, following a truss like pattern. The segments are only supported by their nodes. The research presented here has been initially developed through teaching in the context of M.Arch Architectural Design (AD) Research Cluster 4. Various research topics are developed by postgraduate students working in teams of three to four people. Previous projects, such as SpatialCurves by Curvoxels (Hyunchul Kwon, Amreen Kaleel, Xiaolin Li) (Figure 1-2) or Topopath by Voxatile (Efstratios Georgiou, Palak Jhunjhunwala, Juan Olaya, Yiheng Y) (Figure 3-4) explore similar discrete methods for robotic spatial extrusion. The last project that will be presented in this paper is developed as a non-teaching based research, and aims to develop a generalised approach to design methods for spatial printing.

In the methodology proposed in this paper, toolpath fragments are used as discrete elements that can be combined together in a limited number of ways. These combinations are informed by design and other criteria, and once assembled, they generate a continuous single path.This methodology is being implemented in a stand-alone software application and plugin for Grasshopper. To build this software as a generally available tool, in-depth technical research was required to establish an overview of the parameters and constraints.

A series of furniture scale prototypes have been developed in this research, aiming to test the efficiency of the design method, as well as the adaptability of the software to geometrical and material limitations.

Figure 1
The Bartlett Ad-RC4 Team: Curvoxels (Hyunchul Kwon, Amreen Kaleel, Xiaolin Li) - 3d printed chair

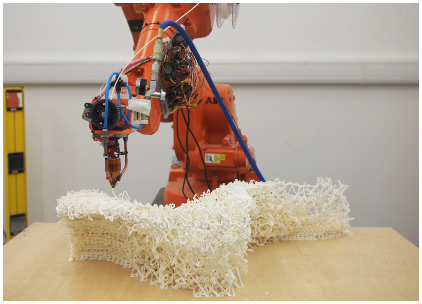

Figure 2
The Bartlett Ad-RC4 Team: Curvoxels (Hyunchul Kwon, Amreen Kaleel, Xiaolin Li) - Robotic 3d printing

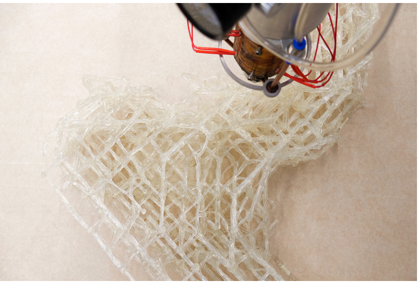

Figure 3
The Bartlett Ad-RC4 Team: Voxatile (Efstratios Georgiou, Palak Jhunjhunwala, Juan Olaya, Yiheng Y) - Robotic 3d printing

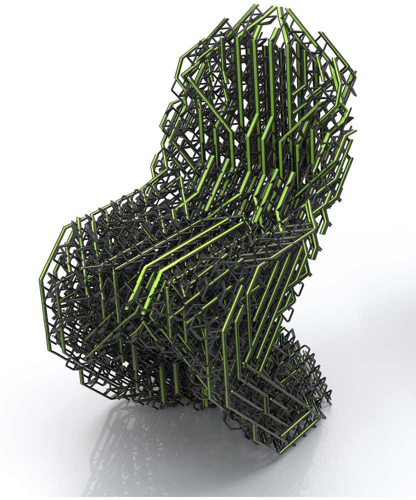

Figure 4
The Bartlett Ad-RC4 Team: Voxatile (Efstratios Georgiou, Palak Jhunjhunwala, Juan Olaya, Yiheng Y) - 3d printed chair

This paper aims to give a wide and reproducible overview of the technical background of the software. It explains the relation between the plastic extruder, material, robotic manipulator and computational process. Based on this framework, a beta-version of the software has been developed, and a first prototype fabricated.

BACKGROUND

FDM (Fused Deposition Modelling) is one of the most common technologies available for affordable, small scale 3D printing. In 2009 the FDM patent expired. Since then, there has been active experimentation with this technology, implementing it in unusual ways.

With the aim of scaling up FDM technology, there has been significant research into large-scale 3D printing processes with industrial robots. These robots were initially used to deposit materials in a layered manner. For example, research at IAAC by Marta Male-Alemany looked into 3D-Printing with clay. It can be argued that the properties of the robot to move along six axis are not really capitalised on in these examples. In recent years, research has aimed to make use of some of the freedoms given by robots, that do not exist in 3-axis machines. These spatial extrusion methods are based on a plastic extruder, mounted on a robot arm, that extrudes a material along a spatial vector.

This method has been initially explored by IAAC, making use of a composite resin (Mataerial, 2013) and at the ETH, with the Mesh Mould project (Hack, Lauer, Gramazio, Kohler, 2014). In comparison to layered methods, spatial extrusion is more time efficient. However, the method has a number of limiting constraints, the most important one that the robot can never intersect previously deposited material.

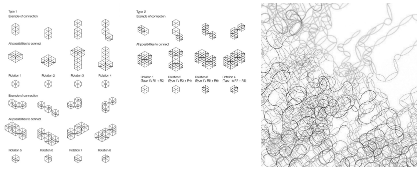

Figure 5
The Bartlett Ad-RC4 Team: Curvoxels (Hyunchul Kwon, Amreen Kaleel, Xiaolin Li) - Discrete toolpath diagram

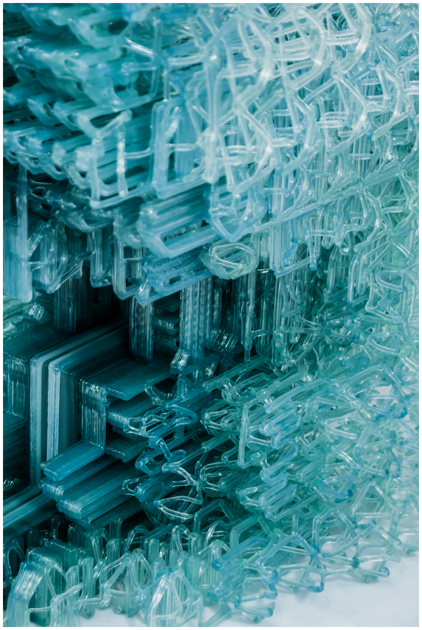

Figure 6
Discrete Computation Lab - VoxelChair v1.0 - detail

There are also structural constraints: material can only be extruded in the air for a limited range - at some point support structures are needed. Therefore, most spatial extrusion projects make use of a highly repetitive toolpath organisation, based on parallel contours, connected by a triangular, truss-like toolpath. The formal possibilities are limited, and the toolpath organisation is not very complex. Complexity is usually a trade-off with speed. As Neil Gershenfeld points out, digital design based on mass-customisation of building elements is caught in a permanent conflict between speed and complexity, and is as well fundamentally analog. (Gershenfeld et al., 2015) To operate in a digital way, machines should operate on materials that are themselves digital - meaning that they are always the same discrete units with a limited connection possibility. (Gershenfeld et al, 2015)

This paper presents a generalised approach to spatial extrusion based on the notion of discreteness. The paper explores how discrete computational design methods offer increased control over the organisation of toolpaths, without compromising design intent and while maintaining structural integrity. The paper then gives an overview of the technical challenges in developing a discrete design software for spatial printing.

DISCRETE APPROACH

A discrete approach to spatial extrusion uses a single toolpath fragment as basic unit for computation. This approach to seriality and discreteness may initially seem antithetical to digital design - and particularly 3D printing (Sanchez, 2014). Digital Design has previously always been associated with continuous differentiation, rather than seriality (Carpo, 2014).

This method increases the efficiency of 3D printing processes by reducing the prototyping phase to a limited number of discrete elements, avoiding the need to compute and test the entire tool path against printing constraints. The possible errors throughout the printed object are not continuously differentiated, but limited and serialised. Printability for the entire object is guaranteed by testing the individual fragments in all possible orientations (Figure 5).

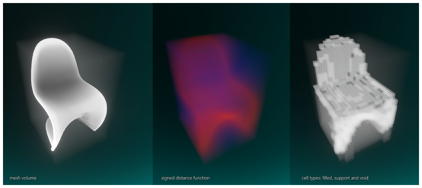

Figure 7
Discrete Computation Lab - Discrete Software - cell types application screenshot

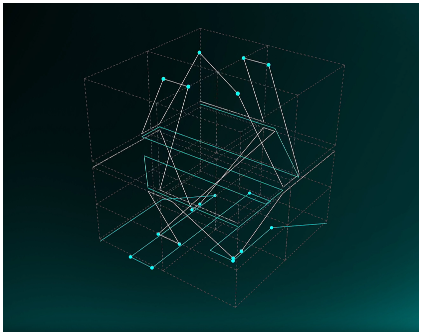

Figure 8
Discrete Computation Lab - Discrete Software - toolpath fragment

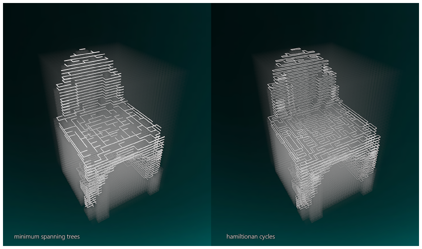

Figure 9
Discrete Computation Lab - Discrete Software - finding a continuous path

This method is based on a voxel space. Each voxel contains geometrical information: one or more toolpath fragments, which are then assembled into a single, kilometers long, continuous extrusion path. The assembly pattern can be designed and controlled in response to different criteria, such as structural performance, material behaviour or more aesthetic design concerns. All of these criteria can be embedded or assigned to the voxel space. This approach is similar to the design of so called meta-materials - synthetic composite materials with a programmed performance that is not found back in natural materials. Formal differentiation and structural performance is

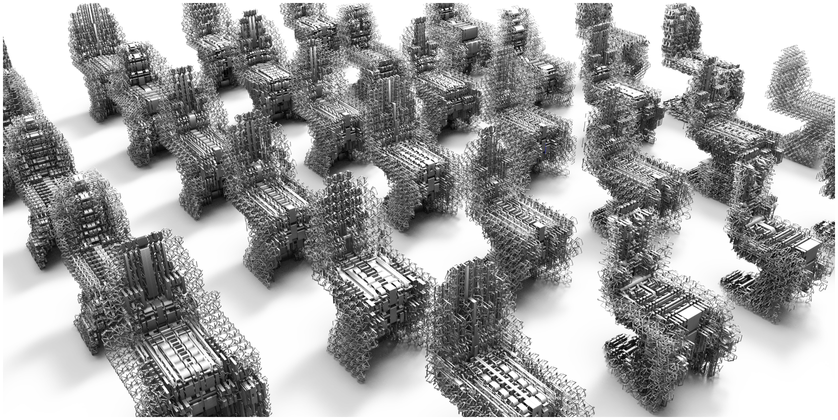

Figure 10
Discrete
Computation Lab -
VoxelChair variants

achieved not through continuous variation of toolpath segments but through the recombination of discrete toolpath fragments.

The computational process begins by defining the volume that will shape the workpiece. This could be any imported mesh object. A voxel space is created that matches the object's shape. This allows for the independent control of the individual voxels, rather than requiring topological manipulations. In fact, once the voxel space is created, the object could be defined as non-topological.

Current developments in voxel-based softwares such as Monolith (Panagiotis and Payne) resonate well with the proposed method, which essentially allows to translate complex, multi-material voxel-data into information that can be fabricated on a macro scale using spatial extrusion with robots. Until now, these type of voxel-based, multi-material prints have only been realised on small scale. However, the proposed method, combining voxel-based modelling with notions of meta-materials and discrete design, opens this domain to large-scale printing.

To optimise the printed mass for large scale objects, a sensible understanding of the scale of the voxels (and its contained toolpath fragment) is needed. This is designed in relation to the limitations of the plastic extrusion, as well as the physical constraints required to create a stable structure. A range of material densities is achieved through the use of the octree subdivision of voxels. This division is defined by performing a structural finite element analysis. This analysis must be performed recursively since any changes will affect the distribution of structural forces. This process leads to the generation of smaller voxels when structural requirements are higher, and bigger ones in those areas where the object can be weaker (Figure 6). This creates a differentiated porosity throughout the entire printed object. There are three types of cells, void, support and filled (Figure 7). Void cells are not extruded. Support cells contain material to be removed afterwards. Filled cells form the actual final result.

TOOL PATH OPTIMISATION - COMBINATORIAL METHOD

An optimal rotation of each toolpath fragment is required to generated a continuous toolpath. This increases the efficiency of the extrusion process, by allowing a continuous extrusion of material, minimizing unproductive robot motions and fabrication errors that appear when the extrusion is interrupted and continued in a different location. (Figure 8) In order to achieve a continuous toolpath, a Hamiltonian path must be found in each of the voxel layers. That is, a path that will visit all cells only once. This is not guaranteed to exist on any arbitrary graph and has a computational complexity of NP-complete (Figure 9).

To guarantee this path to exist, voxels are first grouped into four, forming a larger voxel with four quadrants. These groups of voxels will be culled out or kept as a whole. A spanning tree is calculated from these group of voxels. This is a kind of graph that guarantees that all groups of voxels are connected to each other at least once, and no closed loops are generated. Offsetting this spanning tree to the voxel quadrants (the individual voxels) creates a closed continuous path (a Hamiltonian cycle).

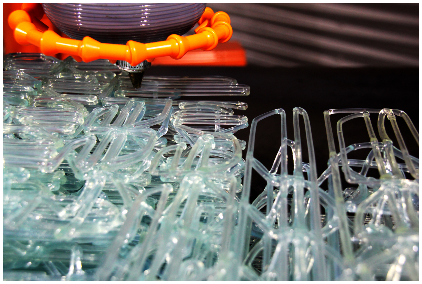

Figure 11
Robotic Extrusion at Nagami

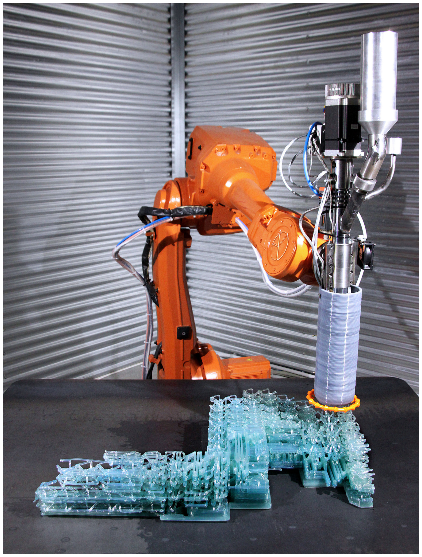

Figure 12
Robotic extrusion at Nagami

To introduce differentiation in material density, each voxel can be subdivided, producing scaled down versions of the fragment paths. The voxel has to still be self-supporting, as the main four opposing corners of the parent voxel are still the only guaranteed supports. The scaled down sub-voxels can't rely on neighbor voxels being subdivided for supporting nodes. The maximum subdivision level depends on the extrusion thickness. The maximum horizontal subdivision level will limit the segments to be at least twice as long as the extrusion thickness. The vertical subdivision is limited to the extrusion thickness itself, creating in essence a conventional layered toolpath at maximum density.

These toolpath fragments are not physical entities, but rather digital units which will be materialised in a continuous printing method. This design method remains close to the notion of digital materials developed by Neil Gerschenfeld at The MIT Centre for Bits and Atoms, where parts that have a discrete set of relative positions and orientations are able to be assembled quickly into complex and structurally efficient forms. (Gershenfeld et al., 2015) However, this is only true for the design method, as the fabrication method is based on a continuous extrusion.

ROBOTIC PLASTIC EXTRUSION

After the path is computed, a robot program is generated that includes additional parameters, such as approach targets, speeds, and commands to control the extrusion flow.

As a test-case to demonstrate the efficiency of the software as a large scale 3d printing tool, a furniture scale physical prototype was developed. This piece, entitled Voxel Chair v1.0, is one of the possibilities abstracted from the 39 first outputs generated using the software. Based on the shape of a Panton chair, these prototypes explore different material distributions and porosities, responding to different structural criteria (Figure 10). Voxel Chair v1.0 was first exhibited at the "Imprimer Le Monde" exhibition at the Centre Pompidou in Paris.

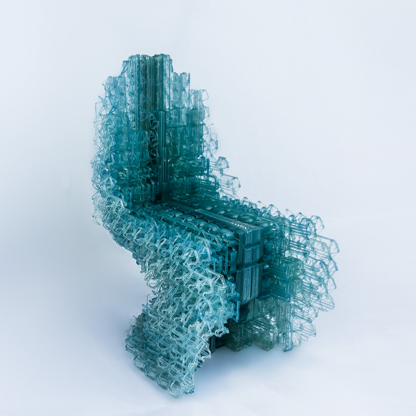

Figure 13
Discrete Computation Lab - VoxelChair v1.0

The prototype was fabricated at Nagami, a small company in Avila, Spain, a company specialized in large scale 3D printing. Transparent PLA pellets mixed with cyan coloring (Figure 11) was used as the extrusion material. The equipment at Nagami consists of an ABB IRB4600 industrial robot with a mounted customized plastic pellet extruder. It uses a stepper motor with an independent controller (not driven by the robot controller) (Figure 12).

The main fabrication errors in the finished product were the deflection of the segments through the extrusion process. This was not consistent, since some deflected more than others and also curved in unpredictable giving the pattern an uneven look. The deflection was still within tolerance, still working properly as supports for the top segments. The chair is assembled out of thousands of smaller toolpath fragments, and then extruded as a continuous, 2.36 km long line (Figure 13)

The extrusion process begins by first having the extruded plastic adhere to the base. The extruder is then moved diagonally upwards creating a segment that is suspended in the air. The extruder nozzle holds the segment by the top end waiting for the material to cool down. After the plastic solidifies, the segment will stay in place only being attached by the bottom node, which is acting as a rigid joint. The extruder is now free to extrude an additional segment without having to support the previous one. The top ends of the segments will become support for additional segments extruded on top (Figure 14).

SOFTWARE IMPLEMENTATION

A programming library and application are produced that implement this methodology (Figure 6).The programming language used is C and the library targets .NET Standard 1.0. This library can be used on multiple platforms where the .NET framework is available, such as Windows, MacOS and Linux. For the application, Unity, a video game development platform was used as the front end for its built in graphics engine, interface creation and cross platform publishing. A secondary library is created to mediate between the Unity C scripts used as the front end and the programming library containing the core logic. This application is available in MacOS, Windows and Linux.

CONCLUSION AND FUTURE WORK

The computational process assumes the extrusion equipment is reliable enough to produce a constant and predictable result. This was not always the case, changes in temperature and other exogenous factors cause the extruded segments to behave unpredictably. Extruding the same pattern multiple times caused non repeatable mistakes. We believe the computation process is valid and the main factor to improve is the use of better engineered equipment. Tolerance parameters can be further tweaked to avoid critical failures, like a collapsing structure, but this will have an effect on the cleanliness of the final object and speed. The volume of the supporting structures can be minimized. We plan to implement a branching structure for this.Currently there's no feedback checking for deviations and deflections of the extruded structures compared to the digital model. We plan to investigate this in a closed loop systems using different types of sensors, including force torque sensor, depth sensors and camera systems that make use of advanced vision algorithms.In addition to the software application, we plan on developing a plugin for Rhinoceros 3D / Grasshopper.

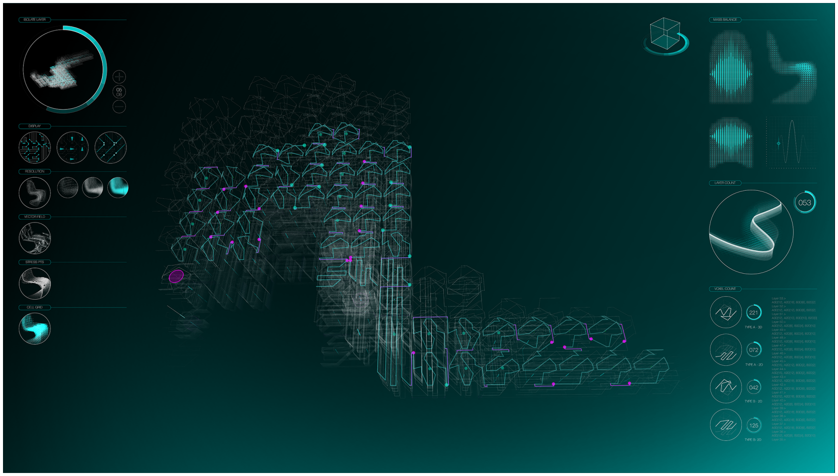

Figure 14
Discrete
Computation Lab -
Discrete Software -
Interface

We can use the core library without any changes as Rhino 3D is extended through plugins using the same .NET framework. Through this plugin, users will be able to design directly the shape of the toolpath, without the need of importing a mesh object. Users will have finer control on how structural and other properties have an effect on the toolpath. They will be able to transverse through the design space quickly, exploring how changes in parameters can influence the aesthetics of the different toolpaths, giving them more control over the final output. Our approach of variable voxel density, using a single material to void ratio, allows for multi-material data to be 3D printed in large scale through the process of robotic spatial extrusion.

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