AUTONOMOUS AGGREGATION-BASED BUILDING SYSTEM

AN ALTERNATIVE TO LARGE SCALE 3D PRINTING

« The Newtonian paradigm places the emphasis on external forces: gravity, natural selection, the market, and so on. Taking nonlinearity into effect means we concentrate more on the system: in evolution the developmental system of the organism, in economics the nature of society and the people who make it up. It does not, as do relativity and quantum mechanics, introduce entirely new scientific principles, but it can completely alter the direction of our research all the same. »

- Peter Saunders[1]

DEALING WITH THE UNPREDICTABLE

Dealing with unpredictable materials and emergent systems has been at the heart of an important number of Architectural research projects over the past ten years. The study of natural systems and how they could influence the way we design our own human constructions brought a new paradigm to architecturaldesign: we do not have to design everything in a top down approach, we can choose instead to declare a set of rules for a system and then let the system itself determine its evolution. René Doursat, Hiroki Sayama and Olivier Michel theorize the role of these potential *meta-designers* in *A review of morphogenetic engineering*: "meta-designers will focus on creating local mechanisms that allow small agents or components to assemble, coalesce, grow, or generate architectures by themselves."[2]. It is obvious that the development of computer simulations has been a major factor in that shift, allowing the interaction of a large amount of discrete elements, often referred to as *agents.* Simulations based on this principle are commonly known as *Multi-agent Simulations*, in which, because we only describe the rules that guide individuals, we can only roughly predict the global behaviour of a *swarm*, thus the exact position of an agent at a given moment in time, *t,* remains unpredictable. The emergent complexity of such a stochastic approach generally offers a positive and a negative side for architects and designers: a high degree of redundancy and self-organization on one hand, but a problematic fabrication process due to the abstract geometry of the resulting forms on the other. For these reasons, working directly on concepts such as redundancy, self-organization and, as will be discussed here, aggregation, within

1 SAUNDERS Peter T, DI CRISTINA Giuseppa (dir), «Nonlinearity. What it is and why it matters», Chichester, *AD Architecture and Science*, Wiley-Academy, 2001

2 DOURSAT, R., SAYAMA, H. & MICHEL, O. (2013) A review of morphogenetic engineering. *"Frontiers of Natural Computing" (FNC 2012) Special Issue*. Lones, M., Tyrrell, A., Stepney, S. & Caves, L., eds. *Natural Computing* **12**(2): 517-535, p.531

the fabrication process seems a more logical approach than designing using multi-agent systems and only posthumously trying to recreate the form as accurate as possible. This last approach is in fact highly contradictory and raises a lot of questions, such as; When should the simulation be stopped? Do we have to build the resultant form exactly as-is? Is there a disparity between the simulated material's behaviour and the real one's? Etc.

Recent research on large scale 3D printing[3] leads us to believe that additive manufacturing will be an important breakthrough for architecture. This process shows a lot of advantages from the removal of the need for formwork to an increased freedom in the shapes' definition (which together give rise to the possibility of optimizing the topology of the elements produced) and eventually to an autonomy of the construction process. But it also comes with a few inherent disadvantages given that the printing process in itself is slow, elements needs to be factory-made with heavy equipment, the machines' building envelopes are limited and it is difficult to make it bigger once it has been built. The system that will be presented here, referred to as Autonomous Aggregation-based Building System (AABS), does not claim to overtake large scale 3D printing, it should simply be seen as an alternative to this type of construction process and strives to prove that additive manufacturing doesn't necessarily have to mimic the increasingly familiar desktop 3D printing workflow or even use continuous material like melted plastic, concrete or clay. Practically, the AABS consists of building a given shape by dropping singular aggregate elements with a cable robot. As we know, the unpredictable nature of aggregates can induce errors in the creation process: an element could down, it could bounce off its target instead of hooking on, etc. Therefore the system requires a real-time feedback of the construction process in order to control and correct the unexpected behaviour of the aggregates. The best way to do this is to use computer vision, a branch of weak artificial intelligence that uses sensors to acquire optical data (colours, shapes, depth by means of infrared rays…) in order to interpret its direct environment.

The whole system can be divided in four parts:

- Construction (Aggregate definition and fabrication)
- Hardware (Cable robot operation and instruction sending)
- Software (General User Interface and generic shape discretization)
- Artificial intelligence (Computer vision and error correction)

3 For an example see: Yingchuang New Materials, the chinese company that printed 10 houses in a day using large scale concrete printers.

CONSTRUCTION (AGGREGATES)

Several design and architectural experiments have already dealt with aggregate structures in the past few years, serving, in fact, as the starting point for the broader scope of this project. Among others, Karola Dierichs and Achim Menges provided a very complete work about the physical behaviour of cohesion-based elements at a microscopic scale for their research on aggregate structures conducted at the Institute for Computational Design, University of Stuttgart[4]. Minimaforms also worked on laser-cut and hand projected aggregates for the stage design of a concert during summer 2014.[5] Another work, that uses clay, offers a very similar approach in the machine vision feedback loop and aggregation-based construction system: Remote material deposition by Gramazio & Kohler Research.[6] As the system exposed in this paper needs to be generic, such as most additive manufacturing processes, the aggregates' shape, material, and cohesion method can all be variable. Just as desktop, filament 3D printers were originally developed for basic ABS or PLA but can actually use a large variety of different filaments from tensile plastic to carbon fibre, wood or metal based composites. Nevertheless, for testing purposes and in order to demonstrate the concept of the system, the robot needs basic aggregate elements to deal with so a first solution has been developed based on mechanical aggregation. The different criteria that have been taken into account so far deal mainly with optimization of the fabrication process: producing the highest possible number of modules at the lowest cost and machining/assembly time while maximizing the cohesion power of the aggregates through their geometry.

The method used to find the best possible geometry of the aggregates was based on a fitness analysis through a high number of physical simulations. Three families of wireframe parametric geometries (star-like forms, pyramid-like shapes and branch-like structures), each of which contained six different variations were tested in a proprietary benchmark, developed in Unity3D, to define a fitness value. This benchmark ran in two sequential iterations, ten generations of ten modules dropping for a first, then a hundred generations of fifty modules for the second iteration. Once the two best module options were identified, a second phase consisted of designing three different modules (for three different types of density) in a more detailed way based on these results which revealed the potency of using a hook and loop typology, just like hook and loop fastener, in order to maximize the cohesion. A new physical simulation set was then conducted to determine the

4 See the two following papers: DIERICHS Karola, MENGES Achim, Aggregate structures. Material and machine computation of designed granular substances, Institute for Computational Design, University of Stuttgart, John Wiley & Sons, 2012 DIERICHS Karola, MENGES Achim, Material Computation in Architectural Aggregate Systems, Institute for Computational Design, University of Stuttgart, ACADIA 2010

5 This project can be seen on the Minimaforms website : http://minimaforms.com/imogenheap/

6 This project can be seen on the Gramazio & Kohler Research website : http://gramaziokohler.arch.ethz.ch/web/e/lehre/276.html

best possible size of hooks and loops. The aim of this second phase was also to make the shapes easy to produce with a laser-cutter. In the end, each aggregate was made of three planar, slotted cardboard pieces and the cutting and assembling process took about two minutes per module for a bounding box of 15x15x15 centimetres and minimal material costs.

This fast and cheap solution served well for testing purposes but can't be considered a long term material to build architectural objects in itself. There are in fact a very large amount of other possibilities for this, some of which have already been tested like using the aggregation as a substructure for a lycra-epoxy shell that can even be reinforced with glass fibres, while others need more financial investment and research into their application but possess a real construction potential, such as metal aggregates as a support for shotcrete. Although these two options are based on mechanical aggregation, chemical aggregation could be another interesting possibility because it would not require any subsequent solidification.

HARDWARE (ROBOTICS)

The cable robot that is being developed for dropping the aggregates offers several important advantages compared to a regular three axis CNC. For this particular case, the research has been focused on portability, modularity and compactness. All the mechanical parts are grouped inside the robot's head, that way setting up the system in any environment is incredibly easy: you just need to attach the three cables to three points in space (these three points form a triangle that defines the system's working space). The modularity also comes from the fact that there's some space remaining on the robot's head, allowing the user to add three more cables to improve the robot's precision and stability if needed.

The fact that we can arbitrarily define the anchor points and can ignore cable overlay (a problem that plagues cable robots where the cable winds onto itself causing massive imprecision by effectively changing the spindle's radius) is afforded by a servitude algorithm that allows us to avoid absolute coordinates.

. What this means is that the robot's operations are controlled by a feedback loop that determines the difference between the desired action and the actual one. This workflow uses machine vision and is very close to the construction correction routine that was briefly outlined earlier, the only difference here resides in the fact that the vision is not based on the same algorithm. Here, the space and the position of the robot's head are acquired using markers, specific patterns that looks a bit like QR codes.

In order to pick up the aggregates, the robot's pendulous head uses a simple claw at its bottom that is ample thanks to the aggregates' own hooks. It will then drop them one by one, from the bottom to the top. The electronics parts are controlled by an open-source Arduino PCB, so instructions for the motors can be sent using Arduino software or Processing, which, as we will describe in the next section, has its own advantages.

SOFTWARE (GENERAL USER INTERFACE)

In 3D printing, the discretization of a shape and its conversion to instructions for the printer is provided by a software called a *slicer*. As the name suggests it slices a 3D model, typically a .stl file, into a G-code-like file. The user then has two options to execute this code, either transferring this file to the printer via an external storage device or connecting a computer directly to the printer to read the file in real time. Recently, a new generation of slicers have appeared called *voxelizers,* because the discretization of the 3D object file works with voxels (3D pixels) instead of slices. It is an interesting approach, because the printer deals with a three dimensional array of small blocks of material, which makes multi-material model fabrication much more viable.

The AABS needs a constant feedback because it's a dynamic system that can't work with a simple series of linear instructions. Because of that, a software able to deal with real-time environment data acquired from computer vision needs to stay connected to the robot. As it also deals with aggregates of different materials, sizes and densities that are potentially customizable, it was chosen to encode a specific voxelizer software on Processing able to, first of all, guide any user through the different discretization steps, material assignment, and construction settings, then run the robot in real time while returning information and statistics about the construction process to the user. This also allows him to see the disparity between the theoretical model (the system's production target) and the current state of the construction process.

Different voxelization strategies are established, for example, it can be based on a recursion using three sizes of modules, that way the centre of the shape can be filled with large aggregates while the borders can be built with smaller modules, giving a higher resolution finish. Another possibility is to use bigger aggregates at the bottom of the construction, strengthening its base, and smaller aggregates at the top or for crossings.

ARTIFICIAL INTELLIGENCE (COMPUTER VISION)

At the heart of the AABS resides the construction process's artificial intelligence. So far, it is able to detect and deal with three different error types:

(1) An aggregate can fall, miss or rebound off its target instead of hooking on, and stay isolated on the floor.

(2) One or several aggregates can fall, or the target spacing generated by the initial shape discretization can be too wide for the chosen aggregate density, resulting in a lack of density at some points of the structure compared to the ideal simulation.

(3) The target spacing generated by the initial discretization can be too dense for the chosen aggregate density, resulting in emergent artefacts due to a too high amount of modules dropped at the same place.

The computer vision uses two Kinect cameras to scan the environment in real time, this generates coloured points in space, resulting from the interpolation of the camera colors and of the distances given by the infrared ray casting. Every *n* aggregates dropped, the software will isolate the scanned aggregates using their colour (the best way to do that is to use the equivalent of a chroma key) before comparing their actual positions to their theoretical positions to solve errors (2) and (3). Obviously, it is nigh-on impossible to identify single elements from a collection of aggregates, so in order to determine if a target has been missed (error type 2), the software checks its distance to the closest scanned point of the ensemble before filling the structure's holes. We use the same process for the error type 3, but this time the software is also checking the heights of the scanned points to know if some elements have been dropped above the highest targets reached so far, if so, the surrounding targets will be consider as reached already. To solve error type 1, the robot needs to detect and grab one particular module, for which we use a Blob Detection algorithm, allowing the program to identify an isolated object by its outline. After checking if this aggregate is reachable (if the cables are not going to intersect the structure), the robot will be able to grab it and reuse it.

DEVELOPMENT

Of course, the AABS detailed here can be seen as a simple proposal to deal with unpredictable material constructions. It was never desired that any of the four sub-researches that have been presented here be irreplaceable: the aggregates could have different shapes and properties, the cable robot could be replaced by drones or by six-axis robots, the shape discretization could be done with alternative strategies, the feedback loop could use other types of sensors etc. Diversity is in fact encouraged as it keeps pushing this approach further.

The AABS is an interesting proposal because it works in its entirety and therefore proves that it is possible, here and now, to build complex architectural objects at a large scale based on unpredictable materials and local interactions: the user feeds the software some simple rules (an overall 3D shape, a discretization strategy, a variety of aggregates...) and then the system builds on its own, calibrating its actions on a physical feedback and thus allowing the emergence and self-organization of the growing structure.