ADAPTIVE MORPHOLOGIES:
TOWARD A MORPHOGENESIS OF MATERIAL CONSTRUCTION

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8 Artifacts embodying cell densities through a Voronoi scheme

ABSTRACT

Architectural discourse has recently suggested a new material practice derived from advances in the field of synthetic biology. As biological organisms can now be designed and engineered for specific purposes, it is expected that, in the near future, it will be possible to program even more complex biologically based systems. One potential application is to literally grow buildings by programming cellular organisms to fabricate and deposit material into architecturally relevant patterns. Our current design methods do not anticipate the potentially challenging material practice involved in a biologically engineered architecture, where there is a loose and emergent relationship between design and material articulation. To tackle this conflict, we developed SynthMorph, a form-finding computational tool based on basic biological morphogenetic principles. A reflection is offered on its use, discussing the effect of multicellular morphogenesis on the production of shape. We conclude that such a strategy is an adaptive design method in two ways: (a) the mechanics of design using morphological constraints involve a practice of dynamic and continuous negotiation between a design intent and material emergence, and (b) the proposed design strategy hints at the production of a biologically produced architecture, which would potentially behave as an adaptive organism.

1 INTRODUCTION

In the last decade a discourse has emerged within architecture which incorporates concepts and terms from the field of synthetic biology (Beesley and Armstrong 2011; Armstrong 2012; Hensel and Menges 2006; Hensel 2006; Cruz and Pike 2008). The influence is not limited to biological metaphors in architecture (Steadman 2008, 1–8), but extends to suggesting a new type of construction process derived from the direct engineering of biological organisms. The potential convergence of architecture and synthetic biology is compelling and, whilst unrealized, such speculations draw attention to the consequences of a material construction process based on the emergent properties of agents exhibiting life-like behaviors. The range of possibilities afforded by such a paradigm is exciting. Hensel and Menges (2006) consider that the cross-fertilization of biology and architecture may reconfigure current material practices in architecture. The scale of such a biological revolution is paralleled to the one initiated by computer graphics and CAD systems in architecture. Specifically, biological systems offer a new repertoire of shapes and patterns (Mitchell 2003, ix–x) derived from material assemblages which make use of efficient and adaptive structures (Armstrong 2012; Jones 2008).

In this paper we take the speculative discourse of convergence between synthetic biology and architecture as a starting point to develop a design context for the eventual development of biological and adaptive material assemblages. To this end we developed SynthMorph, a software that approximates form through the behaviors of biological agents rather than through geometric rules. In the first section, we offer a brief description of the material practices in both architecture and biology, stressing the need for new design paradigms that respond to a looser relationship between the design process, its mediating artifacts and material articulation. We introduce the dual evolutionary design strategy, which is already employed by synthetic biology and involves the use of computational simulations to describe the behavior of new biological units. We report how we followed this framework to combine a previous exploration of biomineralization and architecture (Dade-Robertson et al. 2013) with the conception and development of SynthMorph. We also give account on its use in terms of design explorations. We finally conclude that the use of SynthMorph can produce an adaptive design method in two ways. First, the mechanics of design using morphological constraints involve a practice of dynamic and continuous negotiation between a design intent and material emergence. Second, the proposed design strategy hints at the production of biologically engineered architecture, which would potentially behave as an ever-changing organism.

2 MATERIAL PRACTICES IN ARCHITECTURE AND BIOLOGY

Sabin and Jones suggest that the spatial study of biological cellular structures prompts reflection on how our design models impact and are influenced by processes of dynamic feedback and reciprocity (2008, 21–23). In this section, we lay out the argument that the relationship between design intention and material articulation is potentially loosened when we design for synthetic biological systems. In making such an assertion, we will outline an approach to biological design called the dual evolutionary strategy.

Although both architectural and biological systems produce form through the interaction of various physical forces, they differ in their particular mechanisms. Biological form-generation processes are generally described as dynamic and nonlinear, whereas macro-level patterns result from the local interaction of micro-level parts. In contrast, traditional architectural design involves the top-down patterning of materials where an external sentient agent, such as the architect, exercises design intent from outside the system. This top-down notion seems to run counter to the understanding that architectural space is produced by the interaction of a series of dynamic factors, ranging from social to economical to political conditions (Lefebvre 1992). A combination of such phenomena shapes the conception of what buildings should address and influences decisions undertaken by designers. Even throughout the life of a building, it is the same combination of factors that reshape the architectural object, pushing a number of modifications that, when observed on a long span of time, make evident the plasticity of the architectural enclosure (Brand 1995, 2–12). Nevertheless, architectural material practice is based on a construction process whereby design has been, until recently, largely conceived separately. Design is currently understood as a geometrical abstraction (Oxman 2010), which requires the implementation of prescriptive mediating processes to communicate intent without ambiguity. Syntactic connections are exhaustively described through a set of projections, dissecting the architectural object into discreet and instrumental representations which prevent misinterpretation (Perez-Gómez and Pelletier 2000, 217).

Conversely, biological shape is not the realization of a geometrical abstraction, but the spatial consequence of chemical reactions at the molecular level. Genetic information can be thought of as akin to computational code, holding instructions for the development of shape in sequences of genetic molecules. When genetic molecules come into contact with a matching chemical substance, known as a promoter, they activate a series of events, which in some cases yield a spatial pattern. Under this model, codifying the shape of a cube would require translating such a geometrical pattern into genetic sequences. These sequences, when activated by the appropriate matching substance, would initiate a set of local microscale reactions that would be translated into the macroscale pattern of a cube. The strategy would require provisions of the chemical and mechanical conditions in the environment to allow for genetic information to be expressed. Given the dynamic and unpredictable nature of such systems, the resulting shape is unlikely to perfectly match an idealized shape, but rather a topological equivalent.

3 A DUAL EVOLUTIONARY STRATEGY: IN VITRO AND IN SILICO

In the context of the speculative discourse framing this paper, current design practices are unsuited to fabricate and assemble architecture using biological systems. We propose that this new process will require a dual evolutionary strategy involving biological experimentation and computational simulation. In this section we review the basic definition of the dual evolutionary strategy in the context of synthetic biology, and outline how it was applied to the development of the form-finding application SynthMorph.

Understanding the mechanisms by which form is articulated in biological systems is challenging. Advances in the field of microbiology have yielded a catalogue of proteins and genes for different organisms, which are correlated to specific behaviors and characteristics.

1 Graphic description of the ten basic morphogenetic effectors. Image created by author, based on original illustration by Jamie A. Davies

In synthetic biology such genetic sequences are considered as functional units, often described as "biobricks," and integrated in registries of standard biological parts (Hallinan, Park, and Wipat 2012, 265). However, the manipulation of biobricks is complex. Counter to what would naturally be expected, combining two biobricks does not result in the simple combination of two behaviors. The interaction between sequences produces unexpected behaviors, which are nearly impossible to predict (Endy and Thomas 2008). Modifying one variable, therefore, has an impact on the performance of other individual variables, and that of the general system.

Designing biological systems is a highly complex process, which requires a negotiation between intended behavior and observed outcomes in early experimentation stages. To address this challenge, Hallinan, Park and Wipat (2012) have proposed a method they describe as dual evolutionary strategy. Under this model, a design prototype for a biological unit is codified and simulated in a computational model, which is a rough approximation based on what is known about the behaviors of individual genetic modules. Then, computational simulations and actual lab experiments are run in parallel. Patterns observed in the biological experiments are used to modify the simulation, creating an iterative process. Findings in each strand inform decisions and modify the design of further lab experiments.

The main purpose of the dual evolutionary strategy is to gain insight into genetic manipulations which are not yet well understood, and to inform the design process through the developed computational logic. This methodology is particularly relevant to the speculative discourse framing this paper, as it allows designers to develop a different relationship between design process and material articulation. Rather than insisting upon the manufacture of a particular form, the process implies a dialogue between the designer and the simulation where emergent and unexpected results are possible and even desirable. We have reported on a previous biological experiment we conducted (Dade-Robertson et al. 2013) which served to analyze the process of bacterial biomineralization from an architectural perspective. Conclusions from that work served to inform our general conception of how biological units evolve to form patterns of material through the process of mineralization. Bacteria constitute very simple single-celled organisms which can be seen as exhibiting behaviors similar to more complex multicellular organisms. In this vein we are using this study to focus on computational simulation by developing a form-finding computer software that simulates simple biological morphologies and enables us to manipulate and intervene in the form-making process through an editor interface.

## 4 SYNTHETIC MORPHOLOGIES: DEVELOPMENT OF SYNTHMORPH

In this section, we discuss the development of SynthMorph, a form-finding software that operates under dynamic biological constraints. The system simulates two main processes, derived from the
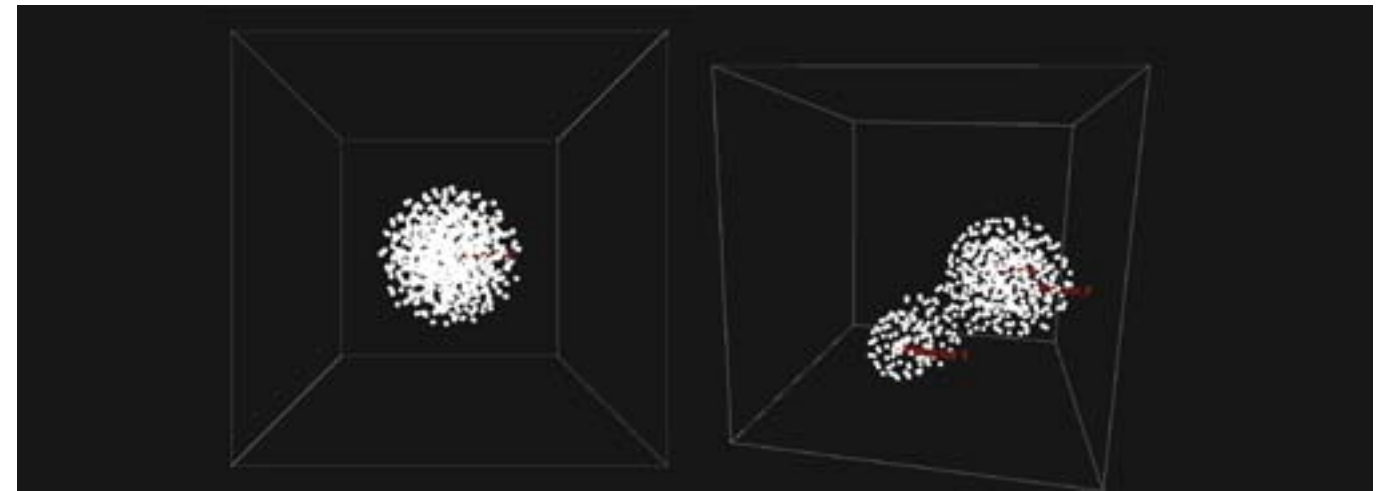
2 SynthMorph showing randomly positioned attractors

study of mammalian morphogenesis (Davies 2008, 709–712) and our observations from experiments in biomineralization (Dade-Robertson et al. 2013). The software primarily models cell behavior in microbial communities, specifically related to cell growth and distribution. In addition, we explore a secondary process of biomineralization through a combination of software and three-dimensional printing.

Professor Jamie A. Davies has proposed ten basic behaviors involved in morphogenesis (Figure 1), which are known as morphogenetic effectors: apoptosis, proliferation, cell fusion, locomotion, chemotaxis/haptotaxis, adhesion, sorting, epithelia-to-mesendnymal transition, MET and folding (Davies 2008, 710–711). He sustains that the development of shape in any biological structure can be described by a sequence of these behaviors. All biological structures, ranging from bones to tissue to branching conduits in kidneys, are articulated by specific morphological permutations in precise combinations (Davies 2008, 710). Following this work, SynthMorph codifies four of the morphogenetic effectors proposed by Davies: namely, apoptosis, proliferation, adhesion and locomotion. Apoptosis conveys the process of programmed cell death, which is understood as the normal process of a cell's life cycle. Proliferation refers to cell reproduction by means of division. In adhesion, cell communities employ a number of adhesion molecules to generate a connecting structure. Finally, locomotion refers to the capacity of a cell to traverse their medium by various mechanical and chemical devices. Although the theory proposed by Davies is specifically contextualized to the field of mammalian development, it has been suggested it also constitutes a foundation for the development of a "synthetic morphology" (Davies 2008, 707). Such an assertion implies that the combination of morphogenetic effectors may not only provide a basis to codify cells into arranging themselves into complex patterns, generally associated with mammalian anatomy, but also to more simple emergent patterns such as the ones observed in the biomineralization exper-
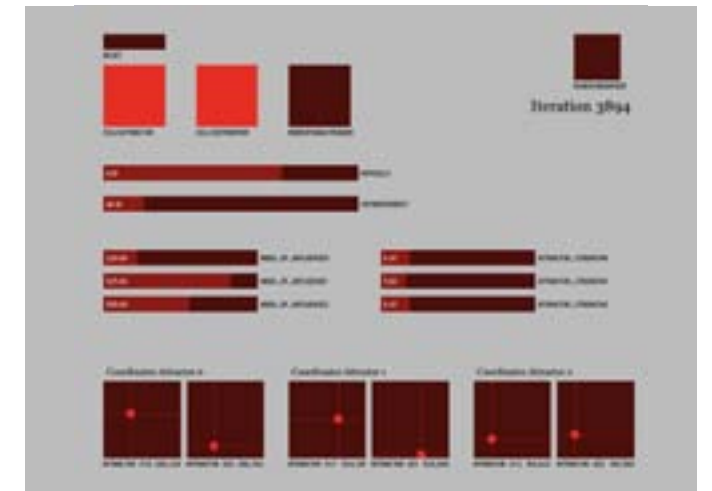
3 SynthMorph graphical interface, showing controllers for area of influence, strength and attractor coordinates

iments we initially developed (Dade-Robertson et al. 2013).

The software described in this paper was developed using Processing IDE and follows the algorithmic structure of a physics-driven particle system. Processing is a graphic-oriented programming environment built on Java. Originally conceived as a tool for artists, Processing was first developed in the MIT Media Lab by Casey Reas and Ben Fry (Pearson 2011). In the following section, we review the algorithmic structure of SynthMorph in detail.
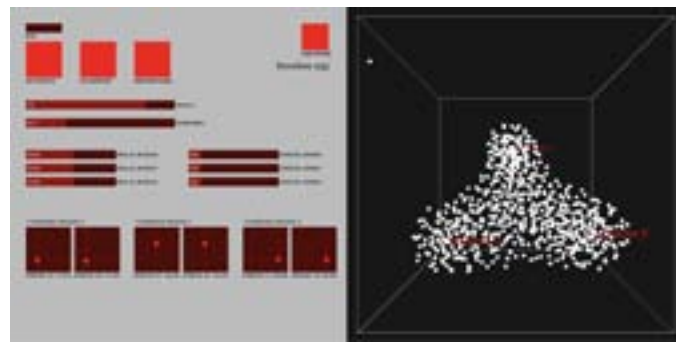
4.1 ALGORITHMIC STRUCTURE

SynthMorph is structured as a particle system using Boid rules, with interaction between particles calculated by a physics engine. Particle-based systems are described as a literal translation of properties exhibited by biological systems (DeLanda 2011, 111–120), whilst providing an efficient structure to describe highly complex and emergent phenomena. Under this algorithm, simple govern-
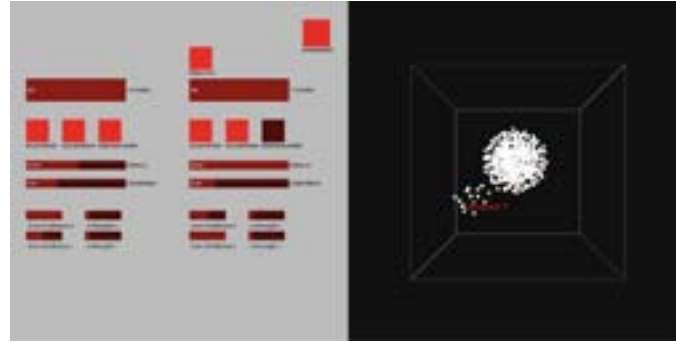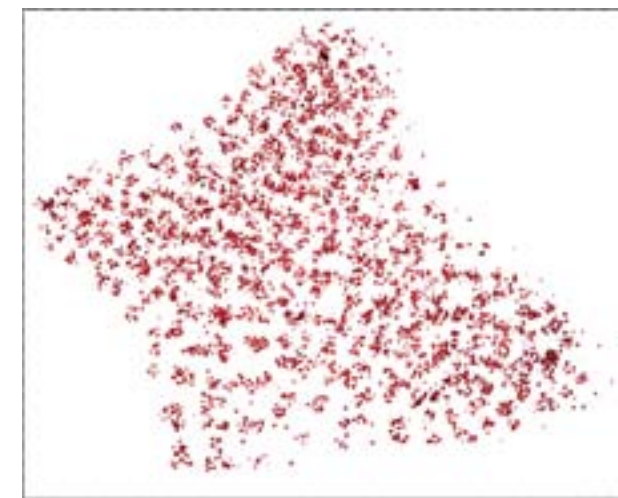
4 AT1-A series, single attractor system depicting area of influence

ing rules are given to autonomous agents, whose positions are calculated iteratively as a result of local interactions (Pearson 2011, 108–112). In addition, we implemented a system of attractors, which are agents that generate a field of influence directing particle distribution. In our model, attractors represent the manipulation of chemical composition in the medium. In a real biological experiment setup, attractors would be equivalent to the focal distribution of nutrients and other chemicals.

Steering behaviors are codified using Boid rules. Originally devised by Craig Reynolds (1987), Boids are used to describe the local interaction between agents in particle systems, such as flocking behaviors. The basic implementation of Boid rules includes a set of three behaviors: (a) separation, the condition to keep separated from other particles; (b) alignment, an average direction based on the state of neighbouring agents; (c) cohesion, an immediate reaction in position based on neighbours' direction (Pearson 2011, 109).

4.2 IMPLEMENTED MODULES IN PROCESSING

Two sets of parameters were enabled in the graphical interface of SynthMorph (Figure 3). The first group was related to the attractors, whilst the second group dealt with cell properties. Attractors were initially positioned randomly in a three-dimensional enclosing space (Figure 2). Users can modify coordinates by manipulating two bi-dimensional sliders for each attractor: the first modifies the XY coordinates and the second changes the XZ positions. Additionally, each attractor was provided with a set of sliders, controlling the area of influence and strength values (Figure 2). The area of influence refers to a volume for each attractor in which other cells are influenced. Strength determines the acceleration that each cell takes when being influenced by the attractor. Chemically, this variable stands for affinity between cell and attraction substance.

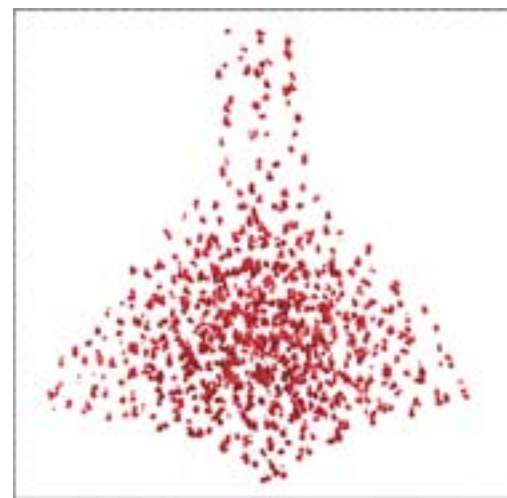5 AT3-C series. The system features an intermediate state between triangle-like and manifold structure

6 Particle distribution in ATF-A series resembling a quadric surface

7 Particle distribution in ATF-C

Cells have four types of controllers. The first control modifies the number of cells within the community, thus simulating duplication. This behavior is codified as an increment in the number of cells, with new cells being placed at the same coordinates as the existing ones. A second control was codified to control the distance between cells to avoid collision. The third control activates the random walk function, which is analogous to the function of motility in real cells. Finally, the fourth control allows users to reset the position of all cells.

Globally, the system was controlled using an iteration counter. Given the time dependency of all biological systems, a display of the time condition within the system was implemented in the graphical interface. Users can know exactly at which point in the simulation the system is currently at, and they can program the system to stop at a particular iteration.

5 DESIGN EXPERIMENTS WITH SYNTHMORPH

This section presents results from the experiments to author specific forms using SynthMorph. The results are presented with the following structure.

5.1 SINGLE ATTRACTOR SERIES

The AT1-A experiment demonstrates the influence of attractors over cell distribution. The spread of cells shows that each attractor generates an area of influence that approximates the shape of a perfect sphere. The Area of Influence variable determines the radius of the sphere of influence, whilst the attractor strength determines how fast each cell is pulled toward the attractor (Figure 4).

5.2 MULTIPLE ATTRACTOR SERIES

AT3-A, AT3-B and AT3-C provide good examples of mutual attractor feedback interaction. Evidence presented by AT3-B as compared to AT3-C suggests that higher attractor strength values lead to a dense distribution of cells. AT3-B is configured with an attractor strength of five and creates a distribution similar to that of a triangle. In comparison, AT3-C with attractor strength set to 2.80 distributes cells in a manifold-based shape. When both variables, area of influence and attractor strength, are set to the same values in all attractors, we observed a more symmetrical distribution. The resulting shape can be described as being an intermediate state between a triangle and a manifold-like structure (Figure 5).

One of the most interesting features arising from the use of SynthMorph seems to be the continuous negotiation between design intent and the emergence of shape in the system. In ATF-A, we aimed to reproduce a quadric surface using four attractors (Figure 6). Values for each attractor were interactively tuned to approximate the desired shape. ATF-B and ATF-C used a five-attractor system to reproduce more complex shapes. In the case of ATF-C, we intended a cell distribution akin to a pyramid (Figure 7). Two features are challenging in the process of negotiation between intent and emergence: understanding the mechanics of fine tuning values

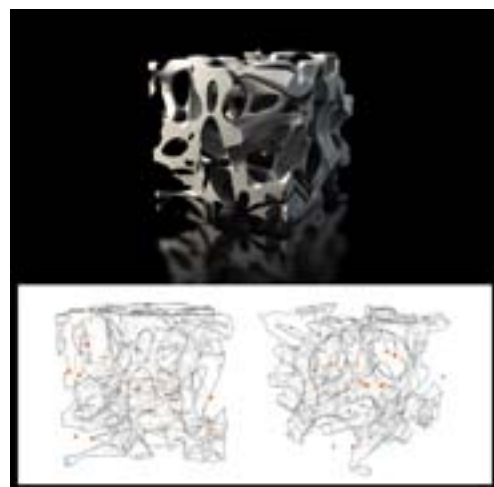8 Artifacts embodying cell densities through a Voronoi scheme

9 Particle distribution in ATF-C

10 Artifacts serve to illustrate the process of physicochemical interactions at nucleation sites

11 Computer-generated imagery showing the relationship between particle distribution (taken from AT1 series) and material configuration

12 The particles generated in SynthMorph, shown in orange, operate as nucleation sites for deposition of material
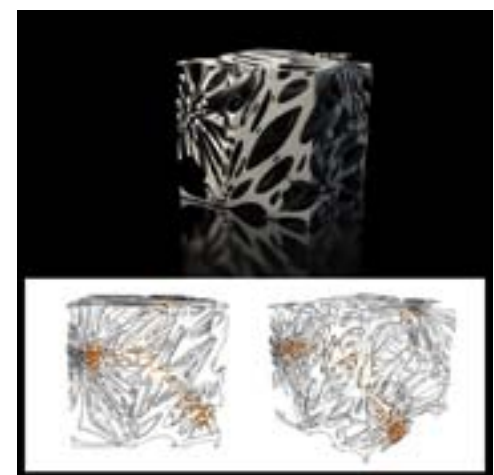
13 Multiple particle system showing mutual feedback in the formation of material

and the dependence on time frames. The latter is especially relevant in maintaining a constant shape. Given the nature of a dynamic non-linear system, the simulation is continuously evolving; therefore, it is difficult to attain a sharp predefined shape.

This section has outlined some of the initial considerations that stem from working with a software designed to approximate the dynamic, nonlinear nature of biological systems. As suggested, SynthMorph is intended to simulate cell distribution, creating a design context for the development of biological morphologies.

6 PHYSICALIZING: PROTOTYPED ARTIFACTS

The secondary process, biomineralization, is implemented through a framework to physicalize densities of cell distribution using a Voronoi algorithm and rapid prototyping. In our previous work (Dade-Robertson et al. 2013), we had conducted lab experiments which revealed how, in the process of biomineralization, the cells provide the trigger for a material fabrication process in the extracellular matrix (the space outside the cell). A similar process can be seen across a range of complex and simple organisms, from mammals to bacteria. In each case the soft cellular material creates an extracellular matrix, which enables crystalline material to form and be shaped (Dade-Robertson et al. 2013). Following these experiments we developed a series of computational simulations that would allow us to explore a connection between cellular growth and distribution, using the morphogenesis development in SynthMorph and the formation of an extracellular material indexed to cell cluster density.

To do this we developed a simulation in Grasshopper, a visual programming environment for McNeel's Rhino 3D. The point cloud distribution obtained in SynthMorph was exported from Processing as a list of three-dimensional positions, which were used to produce a spatial pattern based on Voronoi-Delaunay tessellation. Voronoi is a geometric construct for spatial optimization that allocates the optimal area around a set of points. Voronoi has been widely used in the field of digital morphogenesis, specifically in a bid to invest design outcomes with a high-level visual resemblance to biological systems. Such practice should be understood from the wider perspective of biomimicry, defined by Steadman (2008) as an analogy concerned with the imitation of aesthetic patterns found in nature. The work described in this paper seeks to develop a design strategy based not on the effect but on the processes at work in morphogenetic systems. In this context, Aurenhammer describes Voronoi as a mathematical abstraction initially devised to describe the internal structure of crystals based on the spatial formation of crystals from physicochemical interactions around nucleation sites (1991, 350–351). The scheme therefore produces topologically similar domains of action around a set of points, consistent with the spatial formation of crystals. Considering the initial motivation for this work in biomineralization, Voronoi was deemed relevant to embody the relationship

14 Geometry derived from cell cluster density using SynthMorph

between the spatial organization of the cells and their potential spatial effect on mineralization.

Geometries resulting from the use of SynthMorph were then prototyped using a selective laser sintering machine (Figures 8 and 9). In total, four variations were prepared for further study. One illustrated a system with only one attractor, whilst the remaining three were a progressive evolution of the same three-attractor system at three sequential stages of evolution.

It is interesting to observe the relationship between the design process in SynthMorph and the artifacts presented in Figures 11, 12, 13 and 14. Densities resulting from particle distribution can be interpreted as a design context for the generation of shape. We may describe this concept as scaffolding which sustains the appropriate patterns in space. Material is deposited around the centers created by the particles. We can then interpret the resulting figures as a manifestation of the seams between particles interacting with one another. The resulting artifacts should nonetheless be understood as an exploration of the current difficulties that result from spatial design that operates under a biologically oriented paradigm rather than as a formal outcome of the use of SynthMorph. It specifically illustrates the series of arbitrary design decisions which are required in order to bridge the gap between molecular scale, in which the biomineralization experiments operate, and anthropometrically relevant artifacts. For instance, the artifacts are constrained to a cube shape because it is the most stable way to implement the tessellation algorithm and to later fabrication. This contrasts with the irregular structures observed in natural formation of crystals, even when observed at a macroscale. Additionally, the extrapolation which is made between a scale of micrometers to one in the order of tens of millimeters also results in a loss of the fundamental mechanical properties observed in biomineralization processes. Although biomineralization processes result in the creation of strong structures such as bones and marble, the artifacts show a brittle consistency in some parts of their structure.

The implementation of the dual evolutionary strategy supposes the use of computational simulation and artifacts, such as the ones presented in this paper, in a continual feedback loop which allows the designer to understand the implications of working with biologically engineered materials before it is technically feasible. In this context, the artifacts are proxies, which stand in to simulate and explain natural processes of form generation with a view to substitute them as the development of synthetic biology practices advances further.

7 CONCLUSION, DISCUSSION AND FUTURE WORK

In this paper, we described the development of a design framework that illustrates an adaptive design process for the generation of form. SynthMorph, a core component of this practice, is a computer-aided form-finding software based on principles of morphogenesis. Instead of using a language of geometrical abstractions to convey design intent, we explored new ways in which we could describe a dynamic system. Inspired by the work of Professor Jamie Davies (2005) in developmental biology, we designed a further implementation on the interface based on the paradigm of describing shape through an ordered sequence of morphogenetic effectors. This iteration of SynthMorph allowed modules to be specified on an ordered activation sequence. Our ambition was that this implementation would contribute to finding common ground between architecture and biology.

Some interesting observations came from developing and using this prototype software. By following the principles of morphogenesis, the order in which modules are activated significantly affects the resulting shape. Rather than geometrically defining shape, the use of SynthMorph software engages the designer in a dialogue with the system to tune a shape by altering the state space of the cells. This design process hints at a practice where the designer must mediate between intention and emergence. The design outcomes presented in this paper put in evidence the difficulty of a direct translation between geometrical abstraction and biological shape. Instead, they require a conceptualization of shape as a process rather than as a finished state. More importantly, the design practice that emerges from the use of SynthMorph suggests that the biologically engineered architecture should incorporate strategies to deal and use unexpected outcomes to its advantage.

Design explorations reported in this research pose a number of questions as to the development of a biologically engineered architecture. For instance, we used a process of rapid prototyping to visualize and embody cell distribution and densities in the material articulation of biological form. However, the artifacts presented in this paper are a shortcut from cellular processes observed at the molecular scale to macroscale material formation. Nonetheless, SynthMorph serves as a design reflection on the implications of an adaptive architecture, which prompts a discussion of how we imagine and describe an architecture based on conditions of change.

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