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Biological Pattern Based on Reaction-Diffusion Mechanism Employed as Fabrication Strategy for a Shell Structure

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Biological Pattern Based on Reaction-Diffusion Mechanism Employed as Fabrication Strategy for a Shell Structure

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Abstract. This paper examines how generative architectural design processes aim to apply the principles of biological morphogenesis to the design and building of mechanical or architectural structures. Despite the revolution in computation aided design and interdisciplinary upgrades of digital fabrication technologies, design processes fail to acknowledge materials, tools and construction logic in an early design stage, as manifested in nature. The objective of this paper is to introduce a design workflow, based on the knowledge of the tool, material properties, design intuition and aesthetic criteria, to translate biological skin patterns to fabrication processes, incorporating three materials and procedures in a single parametric workflow. Mesh relaxation processes and weighted mesh graph representations are examined as design potentials for stripe organization in fabrication in analogy to numerical simulations of a reaction-diffusion (RD) mechanism. A thin shell and landscape emerge as a self-organizing system in equilibrium. The paper argues that skin patterns in fabrication open a new field for interdisciplinary investigation.

1. Introduction

Architectural design processes and workflows are goal-directed and traditionally driven by optimizing the functional requirements and the structural hierarchy of materials. The process of biological evolution, on the other hand, is blind to any future goals and proceeds by tinkering and reusing previous structures, thus being subject to historical contingency. It is impartial to the complex sequences of the synthesis of materials, which are instead integrated in the coherent, non-linear and often self-organized process of morphogenesis [1]. Generative architectural design processes aim to apply the principles of biological morphogenesis to the design and fabrication of architectural structures. However, despite the revolution in computation aided design and interdisciplinary upgrades of digital fabrication technologies, they fail to acknowledge materials, tools and construction logic in an early stage of the design process, as manifested in nature. As a result, the realization of specific fabrication processes and their individual constraints often lead to amendments to an already established workflow by making desperate adjustments to rationalize the design.

The objective of this paper is to introduce a design workflow of three digital fabrication techniques (viz. CNC milling, laser cutting and 3D printing), that integrates material properties, tolerances, constraints, capacities, machine limitations and interactivity for the construction of a shell structure and its landscape. Based on the knowledge of the tool, material properties, design intuition and aesthetic criteria, the method tries to translate biologically inspired processes to fabrication processes incorporating three different materials and procedures in a single parametric workflow which manifest a unified patterning system. Motivated by the work of Marc Fornes [2], stripes have many advantages as a construction logic, like minimizing of material and connections, assembly efficiency and structural stability, besides aesthetics and unlimited variations evident in nature. This review first examines biological mechanisms that generate those type of patterns and the available simulation models and computational tools to generate them, as exhibited in biological systems. Secondly, describes how those patterns are incorporated in a form finding process for fabrication. In addition, a qualitative comparison of the shell analysis model, stress lines diagrams, segmented stripe pattern and the physical prototype, offers some potential hints of extracting useful information about stress lines/segmentation relation, skin/stripe performance, structure/landscape continuity and other possible fabrication processes.

2. Reaction-Diffusion (RD) Mechanism and Stripes

Although little is known about the underlying molecular mechanism, many theoretical studies suggest that the skin patterns of many animals are produced by a Reaction-Diffusion (RD) mechanism: a biochemical system involving two interacting diffusible molecules, an activator and an inhibitor, whose dynamics produces putative ‘waves’ in the spatial concentration of each molecule, thus generating periodic patterns in the field [3]. Alan Turing’s theory of morphogenesis [4], based on a RD mechanism, explains the formation of different striped and dotted patterns in a variety of organisms. Mathematical analysis shows that a RD mechanism can generate a wide variety of spatial patterns by varying the few parameters involved, giving this model the potential for application as an experimental working hypothesis in a wide variety of morphological phenomena [5]. The formation of pigmented biological patterns (figure 1), like the stripes or dots on furs, the rings on butterfly wings, the skeletal elements in vertebrate limbs, the scutes in turtle’s shells and even the cusps in mammalian teeth, has become accessible to modelling by means of certain RD equations [6].

There is clearly a connection between natural patterns formation and the RD mechanism. But how this mechanism could be computationally applied to generative architectural design and especially as fabrication procedure? From a scientific point of view, RD simulation is much easier in 2D than other phenomena occurring in 3D [7], revealing a surprising variety of irregular spatiotemporal patterns of numerical simulations [8] to apply to the shell surface and landscape.

3. Simulation tools and biological patterns

The idea of comparing systems in biology and engineering dates back to antiquity, but for long time it was mainly thought of just as an inspiration. Only until the discovery of the gene regulatory networks (GRNs) emerged the idea of thinking about biological morphogenesis in purely mathematical terms. This allowed to establish a formal parallelism between the GRN dynamics and the logic gates in computation theory, paving the way for new approaches, such as the introduction of 2D cellular automata [9] for the simulation of biological pattern formation. A sequence of studies about biological pattern formation (most of them based on RD equations) carried on during the 70s were relevant to other related fields, from complex systems and self-organization to synergetic and dissipative structures [10]. In RD mechanisms, as in other kinds of self-organization models, the primary goal is to capture the essence of the system (that is, a simple set of underlying rules and parameters) which account for a seemingly complex biological phenomenon. The rationale for this is not for simplicity’s sake, but to determine the rules of underline complexity [11]. Although a striking resemblance are often found between the biological pattern and its simulation, the actual mechanism of pattern formation has still to be confirmed experimentally by means of empirical studies [12]. The modelling strategy described in this paper can be also viewed, in an Aristotelian way of thinking, as a way of deriving process from fundamental principles. By doing such an abstraction, one can capture the essence and reveal the rules underlying the apparent complexity.

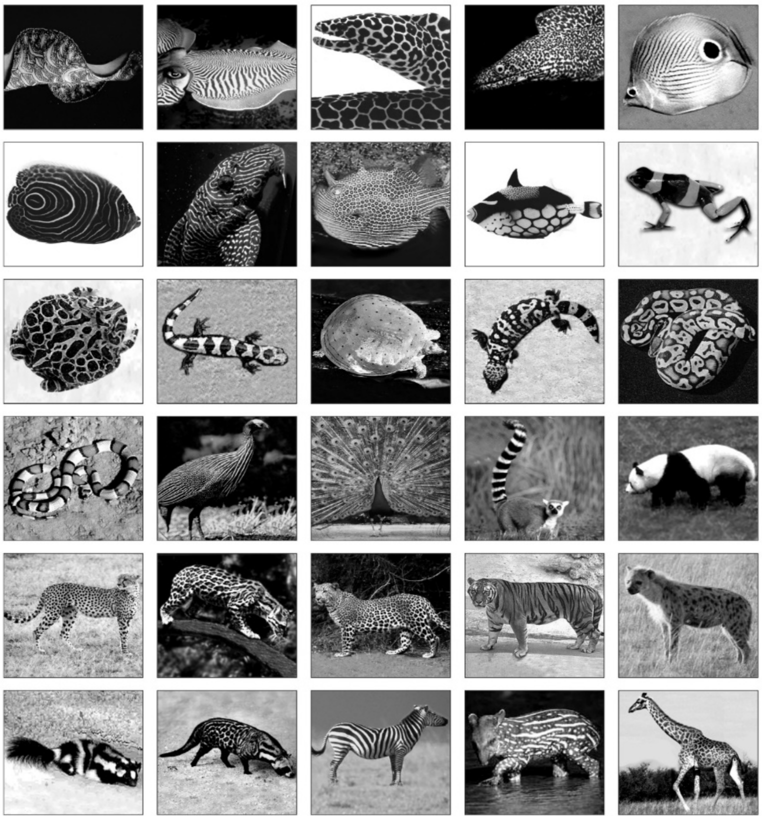

Figure 1. Typical examples of pigmentation patterns on animals [13]

Nowadays, the RD mechanism is computationally accessible, and there are many programming languages, and mathematical models like the Gray-Scott RD model, with the ability to produce a varied number of biological looking (and behaving) patterns, both static and constantly changing to simulate fast and computationally efficient finite difference method for the Turing pattern on curved surfaces in the three-dimensional space [14]. Numerical simulations of a simple RD model reveal a surprising variety of irregular spatiotemporal patterns. (figure 2)

This research demonstrates that an application of weighted meshes representations is suitable for fabrication and provide an efficient design workflow. The network of connected faces and edges of the mesh is a simplified representation of architectonic elements, such as structural framing or facade panels. Recent research demonstrates that approaches bringing together mesh and graph representations drawn from computer graphics can be effective within the domains of applications for which they have been developed [15] [16]. The dual graph concept implemented as a data object called MeshGraph (MGraph) corresponds to the specific purpose of unfolding surfaces and segmentation of triangular meshes. The application is running inside Grasshopper platform and could generates stripe formations in an early design phase, giving at the same time the CNC cut designs and logistics.

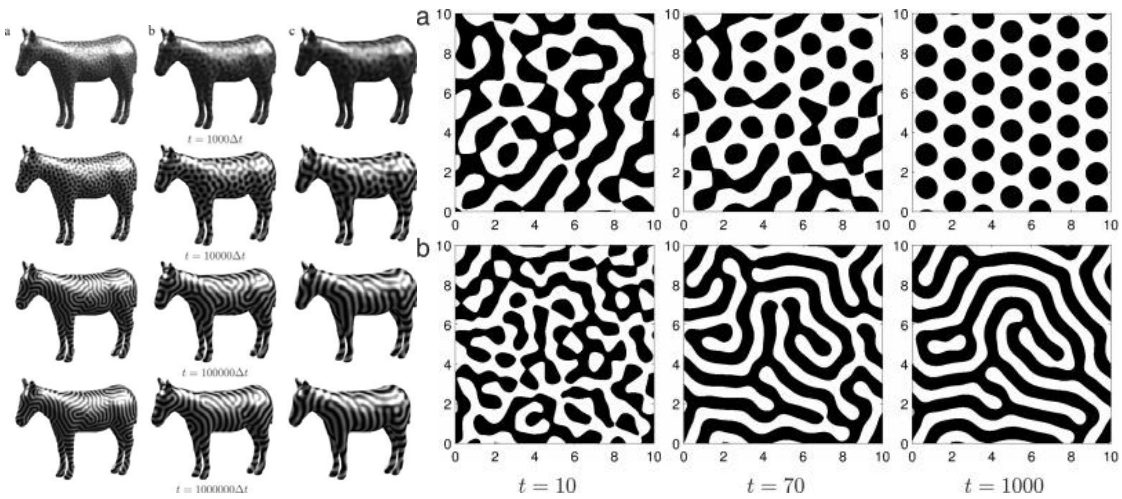

Figure 2. (left) Pattern on two-dimensional rectangular domain, (right) Pattern formation process of the Lengyel–Epstein model on a zebra surface [14]

4. Design Methodology

This research offers a methodological framework of identifying a suitable surface pattern with similar features to a RD-based stripe formation to be used as fabrication logic for the CNC, laser cutter and 3d printer. We computationally explored and geometrically defined the patterning algorithm with explicit reference to biological morphogenesis and Graph Theory. The approach uses force-based relaxation processes for the structure and mesh segmentation algorithms for the generation of skin and landscape pattern. Eventually, to give the stripe effect, the mesh relaxation process is linked with the segmentation process and the fabrication process. Structure, skin and landscape could be one unified system in equilibrium.

4.1 Mesh relaxation process for the shell structure form-finding

To generate, in a simple and intuitive way, a structure in static equilibrium, with minimal surface properties, dynamic relaxation physical load force of gravity (using Kangaroo physics plugin inside Grasshopper) was applied to the initial surface topologies with boundary conditions defined by anchoring points. An organic structural membrane system of planar quadrilateral mesh faces emerged as a result with near zero mean curvature surface properties (not exactly minimal, because other forces are also applied, but could be fixed by applying more strength during the relaxation process). During the relaxation process, the real-time dynamic physics engine allowed to visually and intuitively interact with “virtual” physical forces applied to the pre-defined geometry, translating mesh lines and vertices to a network of springs and particles. The load, spring length and strength is controlled by the algorithm, to generate the proper height of the shell. Piker [17], mentions that the models we use for physical form-finding are usually not simply a scaled down version of the real structure, but involve a level of abstraction. We use materials which are quite different from those we will eventually build with at full scale but have key behaviours and geometric properties relevant to their construction in other materials. The shell structure was generated taking in count material properties of the prototype and fabrication technique.

4.2 Mesh segmentation process for the shell skin and landscape

The project employs computational techniques of weighted-mesh representations for the generation of 2D geometrical configurations of stripe patterns for the surface skin (figure 3) and landscape, analogous to the skin patterns emerging from RD mechanisms. As a construction logic, each stripe is conceptualized as a ruled surface (developable, with zero Gaussian curvature), which is unrolled according to two valence nodes mesh. The relaxed mesh was given as input to the segmentation algorithm to compute the minimum spanning tree for the mesh graph using a modified Kruskal's algorithm with max valence preference. Specifically, the Input parameters were:

- G (MGraph): The MGraph object used for MST calculation
- W (Domain): Optional domain for the weights to be considered
- V (Integer): The maximum valence for the node. This value signifies a preference not a limit
- S (Integer): The maximum number of nodes in one piece. (or number of faces)

The Output parameter:

- G (MGraph): The minimum spanning tree/trees MGraph object, which defined the pattern.

The algorithm was also controlling the amount of mesh faces, that is the size of stripes to appropriately fit to the machine for fabrication. A series of fixed initial anchor points were given as an input for the generation of parallel surface stripes and profile landscape lines. The form-finding of the landscape stripes, followed the same process as the skin, with an additional operation, after the segmentation, of generating 3D wave pattern. The MGraph lines are used as mountain lines and the stripe edges as valleys as appear in the prototype.

Figure 3. Shell model MGraph lines and two valences segmentation

4.3. Fabrication process of the shell and landscape
The entire fabrication process was accomplished in three parts. The outcome prototype, constructed during a five days master workshop, required full coordination between teams, each one responsible to deliver the G-code for a specific fabrication technique.

4.3.1. CNC milling
The landscape stripes were milled on the polystyrene foam using various tools and milling methods (figure 4, bottom right). The profile lines were inputted as tool paths, generated using RhinoCam2016. Several milling operations were used to generate the desired pattern. First, the horizontal roughing with a 50 mm diameter ball-mill with 2 mm stock and 50% step-over. Second, was the parallel finishing with a 20 mm diameter ball-mill with 1.5 mm stock and 50% step-over.

Figure 4. (Bottom right) First milling operation, horizontal roughing, with ball mill (50 mm diameter). Stock of 2 mm and stepover 50%. (bottom left) nested pieces for laser cutting, (top) 3D printing piece

In-order to create different patterns on the first parallel finishing, different milling operations, like radial machining, parallel finishing and 3D offset pocketing were implemented with a 6 mm diameter ball-mill with different step-overs like 200%, 100% and 50%. The 3 mm diameter flat-mill was used to make the hole pattern and 6 mm diameter flat-mill to make the frame using the engraving milling operation. Eventually, the surface that attaches the 3D printed structural legs, was flattened using sandpaper to have stability, ease of drilling and inserting the fisher screws. The entire CNC milling process took 2 days for the result.

4.3.2 Laser cutting

The unrolled surfaces were systematically numbered and labelled to create assembly guidelines after being individually cut (figure 4, bottom left). The triangulation of the meshes further exemplified dashed score lines to add slight flexure to the otherwise stiff polypropylene stripes. After being labelled and scored, the stripes were treated as individual 2D shapes, and additional semi-circular loops were added at the naked edges of each triangulation. At the assembly stage these loops would serve as overlapping washers for screw and nut fixing. The labelled, loop-edges 2D shapes were nested on 1050x750 mm sheets using RhinoNest for optimization of material use and then exported to the laser cutter using Autocad 2007. The 0.8mm thickness of the polypropylene sheets, and the melting point of the material dictated the speed of cutting, the overall outcome and the level of detail obtained. The laser cut pieces were connected to each other, based on the label numbers, and by means of 2.5 mm diameter screws and nuts. Here, the tolerance between stripes could have been adjusted by this diameter. The entire laser cutting process of took 4 hours.

4.3.3 Printing 3D

The 3D printed legs were employed as the structural interface between polypropylene stripes and the CNC milled landscaped polystyrene foam. An additional piece was designed additionally to close the top hole of the shell (figure 4, top). The design of the structural legs mediates between the structural properties of the polystyrene foam and the polypropylene sheets to accommodate their respective design. To avoid over designing and over complication, the structural legs were made to be robust, engineered junction pieces accommodating the sizes of holes for the screw and nut connection. The four designed structural legs were first made to be watertight, by closing all naked edges. To create the G-code, the designs were sliced in Cura Engine and 3D printed using FDM (Fused deposition modelling) additive printing on Felix 3.1 with a build volume of 255x205x225 mm, extrusion speed of 15mm/s and motion speed of 150 mm/s. The material used for printing was PLA(Polylactide) filament with 1.75 mm diameter requiring working temperature of 190-210 °C and platform temperature of 50-60 °C. The structural legs were printed without any supports, directly available for assembly. Although, the screw holes required sanding and smoothing with a drill machine. The entire 3D printing process took 3 days on 3 Felix 3.1 printers for the result.

4.4 Assembly

The four printed structural legs were first mounted on the polystyrene foam by means of fisher screws and had the first connecting layer of the polypropylene stripes securely connected to them. The other layers of the polypropylene were subsequently added based on their labelled numbers. All teams came together in a collaborative assembly process where the sequential roles and responsibilities based on the material were fulfilled. The entire assembly process was finished in 12 hours, without any eventual amendments to the already established workflow. The stripe formations not only generated the shape, but also aided in ease of assembly, thereby reducing time. (figure 5)

5. Discussion

Using generative architectural design processes, the design workflow intends to translate biologically inspired processes with similar features to a RD-based stripe formation to fabrication processes. A qualitative study of the shell FEM analysis model, stress lines diagrams, segmented stripe pattern and the physical prototype, offers some potential hints of extracting useful information about stress lines/segmentation relation, skin/stripe performance, structure/landscape continuity and other fabrication processes.

Figure 5. Prototype model

5.1 Simulation models

From the initial form-finding of the shell with near minimal surface properties, the skin is segmented and constructed as developable stripes using thin planar sheets of material. The landscape is milled, applying similar stripe generation process. The simulations were made as two different stages with different parameters controlling, for the skin and landscape, but it is possible to be in one single. It depends on the computational power available and the fabrication method used. As a discussion we could say that other programming languages could have been used to generate stripe formations. What has been as advantage using MGraph was that allowed the whole process, from concept to fabrication, to be generated inside the same platform, without program exchange complications.

5.2 Structural model

In this project the intention was to examine how a thin shell, constructed by connected stripes, would behave without extra structure but just counting in the equilibrium stage of the relaxation process. A very fast linear elastic analysis of shell element, made with Millepede plugin gives a hint of the spatial distribution of deflection across the structure, suggesting and revealing some of the prototype's vulnerable areas. In relation with the stress lines, we observe concentration of lines on the deflected areas. For the structural model, material data of polypropylene was used (elasticity, density and yield strength [18], and poisson's ratio [19]). Stress (force) lines reveal where the shell could be topologically optimized or accordingly arrange stripes direction for best performance. We observe that in most of the cases stress lines became perpendicular to the stripe segmentation. (figure 6)

Another structural aspect to be considered related to the fabrication process, is that nested pieces, should take in count the material properties when arranged into the material to be cut. A way of arranging the pieces that go against the grain of the wood for example, would weakening them, as happened in the case of Mark Fornes project. [20]

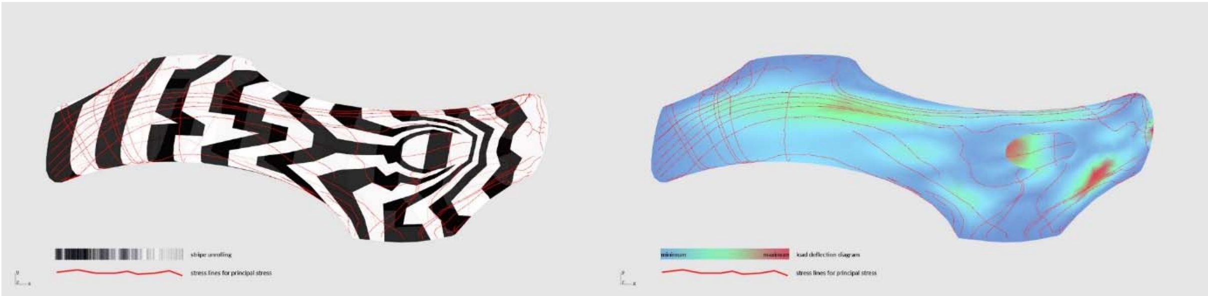

Figure 6. (left) Stress lines in relation with stripes, (right) stress lines in relation with deflection model

5.3 Conclusions and future work

We argue that the proposed method has many design potentials as stripe organization for fabrication, thus opening a new field for interdisciplinary investigation between engineers, programmers and scientists and fabricators. A deeper study of pattern formations and simulation models performed by mathematicians could address insights in the field of adaptive design systems in terms of temporal dynamics of changes in the pattern, as occurs in the skin stripes of fishes formed by waves [21], or the viability of an experimental implementation of 3D patterns with geometrical and topological properties of Turing patterns (area, boundary length, cluster numbering, connectivity, and so on) as described by Guiu-Souto et al.[22] inside a generative fabrication context.

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