Emergent Reefs

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Abstract. The purpose of Emergent-Reefs is to establish, through computational design strategies and machine-based fabrication, seamless relationships between three different aspects of the architectural process: generation, simulation and construction, with the intent of exploiting the expressive and tectonic potential of D-Shape technology for underwater reef formations as a design response to coastal erosion. Starting from a digital simulation of a synthetic local ecosystem, a generative technique based on multi-agent systems and reaction-diffusion (through continuous cellular automata - CCA) is implemented in a voxel field at several scales. Discrete voxel space eases the simulation of complex systems and processes (including CFD simulations) via CCA algorithms, which then can be translated directly to the physical production system, which in case of additive technology can be specified as guided growth.

Keywords. Reaction-diffusion; Reefs; Multi-agent Systems; Open Source; D-Shape.

INTRODUCTION
Coastal erosion is a process that, if uncontrasted, over time leads to sea bed desertification and waterfront thinning, thus involving both sub-marine environment and tourism activity. Italian shores are a typical example: the intensified quantity of tourists in the last decades while giving propulsion to the economy at the same time increased the seabed smoothing caused by tourists, thus easing the action of progressive erosion. Instead of focusing on the solution of the specific problem through existing models and approaches, the intent of this project is to address the issue of a positive environmental transformation through the generation and construction of marine reefs shaped to host an underwater sculpture gallery while at the same time providing the material and spatial preconditions for the development of marine biodiversity on the transformed sea-bed. Tourism becomes a part of the ecosystem; the generation of evolved functional programs, morphogenetic strategies and production technologies are considered efficiently connected nodes of a coherent yet differentiated network. Starting from a digital simulation of a synthetic local ecosystem, a generative technique based on multi-agent systems and continuous cellular automata (put into practice from the theoretical premises in Alan Turing’s paper “The Chemical Basis of Morphogenesis” through reaction-diffusion simulation) is implemented in a voxel field at several scales giving the project a twofold quality: the implementation of reaction diffusion generative strategy within a non-isotropic 3-dimensional field and seamless integration with the fabrication system.

D-SHAPE
The entire project was developed with D-shape fabrication technology in mind [1]. Developed by Eng. Enrico Dini, who patented the technology that solidifies sand through liquid infiltration and built a large scale 3D-printing machine, it extends and scales up
the more common 3D-printing process; D-shape uses the same additive tomographic layering strategy, with sequential layers of dolomitic sand upon which a row of nozzles drop a patented binder liquid only in the corresponding section points. The invention was co-opted from its initial purpose (printing houses) into many different applications, mostly in the field of art (sculptures) and, more recently, marine barriers. Since objects to be produced can have a very heterogeneous generation history, a 3D voxel grid is used to rationalize them to the process and resolution of the machine; this step is not only necessary, it is the principle that links digital processes to the materiality. Nonetheless it is applied in an extensive way: two different models of rationality are overlaid with a brute-force method, but one lacks geometry generation and the other misses the link to material production. As a consequence of this double gap and since the resolution achievable at the moment is quite coarse (in z direction the layer thickness is 5-10 mm and the liquid expansion causes a slightly larger horizontal xy resolution), the emerging pattern is mostly treated as an imperfection and sanded, considering the slick look of the digital model as a finalized result to tend to.

Starting from these assumptions and in the intent of exploiting the expressive and tectonic potential of D-Shape technology, the project explores voxel-based generative strategies. Working with a discrete lattice eases the simulation of complex systems and processes (including non-linear simulations such as Computational Fluid-Dynamics) starting from local interactions using e. g. algorithms based on continuous cellular automata, which then can be translated directly to the physical production system. The purpose of Emergent-Reefs is to establish, through computational design tools and strategies and machine-based fabrication, seamless relationships between three different aspects of the architectural process: generation, simulation and construction, which in the case of D-Shape technology can be specified as guided growth.

**ATTRACTORS**

The idea of an underwater exhibition architecture suggests a general layout articulated as a cluster of heterogeneous and connected halls. Such spatial distribution pattern is typical of a peculiar marine environment, the atoll. In order to generate a similar distribution pattern a strategy based on the interaction with a 3D data field (provided by the simulation of underwater currents) and attractors is implemented: in Complex Adaptive Systems, attractors are points in the space of possible configurations of a system (phase space) representing stable configurations, wether static or dynamic, towards which the system tends, generating stable, oscillating or propagative behaviors [2]. Attractors here represent the halls as stable configurations and let the system work to generate the intermediate states between them.

A software tool was developed in Processing to control the influence of a set of attractor points (using position and intensity as parameters) on density fields. Two different classes of attractors were defined (positive and negative), based on magnetic field laws, moving in a two-dimensional domain. The voxel size (and so local density) is linked to position and intensity of each attractor following an inverse square law:

\[
\phi_A = \sum \pm \frac{P_i}{R_i^2}
\]

where \(\phi_A\) is the density at a specified point A, \(P_i\) is the charge intensity of the ith attractor, and \(R_i\) is the point-attractor distance. The density function influences the height of reefs that can eventually emerge above the water surface. However, it is necessary to introduce a special cut-off condition for higher values in order to achieve the crater-like configuration of the halls system:
If \( \varphi > 1 \): \( \varphi = 1 - (\varphi - 1) \)  

(2)

Working coherently within the voxel grid, a CFD simulation of the underwater currents was implemented (with the help of eng. Diego Angeli, researcher within the Mimesis group at the Faculty of Engineering, University of Modena) through OpenFOAM® (open-source software for CFD analysis) in order to create a data permeated space. The speed vectors data calculated in OpenFOAM is read into Processing via a custom written plug-in; attractors cause directional vector-field convergence and inverse square vector intensity falloff. This alteration differs from a purely responsive behavior in which a system reacts to an existing simulated data field: it is already a proactive operation in order to anticipate effects. It is crucial, however, to coherently define the process of attractors generation and placement.

THE ECOSYSTEM

The adopted morphogenetic strategy for attractors consisted of a virtual ecosystem: while interacting with an underwater environment and simulating distribution patterns, it is possible to stumble upon inefficient configurations with low or undesired capacity of nutrients distribution.

It is therefore necessary to develop a morphogenetic strategy which, starting from the vector field, is able to generate global configurations that are coherent with currents behavior from simple internal local relations. This bottom-up strategy searches global system coherence as an emergent property of agents mutual interactions in the ecosystem or, in other words, as the moment in which the global system reaches and maintains homeostasis. In order to assess the nutrients distribution capacity of the system over time, a transportation algorithm was adopted, with the ability to visualize concentration patterns according to vectors direction. In relation to this environmental property two different classes of interacting agents (A type and B type) are moving in the defined domain interacting among each other via a stigmergy-based relationship. The interaction between the two species occurs through information released in the environment: nutrients released by B type agents are stored in the voxel cell corresponding to the agent position and sub-
sequently transported through the fluid following the currents (vector field directions). B type agents are able to detect nutrients concentration and move looking for higher concentration areas. This evaluation is achieved through the analysis of neighbors cell that return the gradient of density function.

\[ \mathbf{v}_D = c_s \nabla D = \frac{\partial f}{\partial x} \mathbf{i} + \frac{\partial f}{\partial y} \mathbf{j} \]  

(3)

where \( \mathbf{v}_D \) is the movement vector related to density function \( D \), and \( c_s \) is a sensitivity coefficient for nutrients. A positive feedback is enacted: every agent enforces the strongest nutrient paths. In addition to this stigmergic behavior each agent interacts with neighbors of the same kind through the basic flocking rules identified by Craig Reynolds: cohesion, separation and alignment. “A” type agents class is subdivided in two subclasses determined by the sign of \( c_s \) and correspondingly different behaviors: A- (generative) and A+ (dissipative). A- agents search for areas where nutrients concentration is minimum and generate a magnetic-like field (such as those described previously, with inverse-square distance propagation rule) that varies in extension an magnitude according to number and charge of clustering agents, while A+ subclass agents search for areas where nutrients concentration is maximum and can dissipate magnetic field tending to revert the environment to its unaltered state. The usual cohesion and separation rules control density and spatial distribution according to each agent charge intensity. Both subclasses maintain a stigmergic behavior with nutrients spread by B type agents. Each A subclass can switch type (A+ to A- or the other way around) if the nutrient concentration goes (respectively) above or below two limit thresholds that define a “comfort zone” for the agents. Charge intensity of each A type agent represents then both a sort of “health level” and the ability to generate (for A-) or dissipate (for A+) the aforementioned magnetic-like field.

The simulation can be manually stopped when the ecosystem reaches a stable condition; in this case visual assessment is faster than and (for the required accuracy) as effective as coding a stopping condition; not to mention that such implementation, since it requires testing all agents in the system at each step, would have considerably slowed down the whole simulation. While the simulation is running it’s also possible to interactively tweak different parameters and alter or switch the agents’ charges. During some of the simulations, when the density of A- agents in low-concentration areas reached a critical point, closest packing behavior appeared although there is no specific coded implementation of it.

**REACTION-DIFFUSION**

The previous step provides an efficient strategy based on bottom up processes for the generation and spatial deployment of the fields governing the reefs morphogenesis; the morphogenetic process itself is then developed through the implementation of a differentiation process that progressively separates void (passage) areas from those occupied by the material. In order to keep integral and coherent with the field generation and fabrication logic the exploration of cellular automata algorithms, focusing in particular on reaction-diffusion for its properties of condition-based differentiation and articulation in space, seemed an almost natural choice. As hypothesized by Alan Turing (1952) in “The Chemical Basis of Morphogenesis” such algorithms are the basis of morphogenetic differentiation, and can be simulated through a system of two interacting chemical substances, called morphogens, reacting together and diffusing in space or on a surface. The reaction-diffusion process was implemented using Continuous Cellular Automata algorithms over a 3D voxel grid, the same underlying structure that allows a seamless transition through all the steps of the overall process, from analysis to fabrication. Every voxel cell interacts only with its 26 adjacent neighbors. In the case of a simple isotropic pattern, whose behavior is the same in any direction, it is sufficient to consider the 6 main
Figure 2
Examples of different fields configurations emerging from variations in the agents behavior.

Figure 3
Algorithm steps relationship diagram.
neighbors. The remaining 20 cells, with only an edge or a vertex in common, are used in order to implement anisotropic diffusion. Diffusion simulation is solved through a model based on the law postulated by Adolf Fick, which predicts how diffusion itself affects the variation of concentration over time:

\[
\frac{\partial \phi}{\partial t} = D \nabla^2 \phi 
\]

(4)

where \( \phi \) is the concentration as \( \text{[(amount of substances)}/\text{L}^3] \), \( t \) is time \( \text{[T]} \), \( D \) is the diffusion coefficient as \( \text{[L}^2\cdot\text{T}^{-1}] \). The general reaction-diffusion process simulation is based on the Gray-Scott algorithm, applied implementing the equations that, extending Fick’s law, express both reaction and diffusion phenomena:

\[
\frac{\partial u}{\partial t} = D_u \nabla^2 u - u v^2 + F (1-u) 
\]

(5)

\[
\frac{\partial v}{\partial t} = D_v \nabla^2 v + u v^2 - (F+k) v 
\]

(6)

where \( \partial u/\partial t = D_u \nabla^2 u \) and \( \partial v/\partial t = D_v \nabla^2 v \) represent Fick’s second law of diffusion: \( D_u \) and \( D_v \) are the diffusion coefficients of morphogens \( u \) and \( v \) respectively, with \( D_v < D_u \). Through these equations the fields obtained in the previous step are associated with different properties of the two morphogens: the vector-field affects the preferred diffusion direction of morphogen \( v \) while the density field affects the variation of parameter \( k \) for reaction. The term density is referred to the rate of material-filled volume compared to the overall simulation volume. Pattern formation and direction are thus controllable by tweaking the Gray-Scott parameters which act on the outputs of the simulated ecosystem, coherently exploring variation at the present system scale.

**LAYOUT PATTERN**

The importance of anisotropy in patterns distribution arises from several necessities: avoid reef overturning, coordinate scuba divers trajectories and underwater currents with the reef formation itself in order to minimize human-reef collision chances (as cross-directed currents would push divers against the reefs) and provide a distribution system of “cor-

Figure 4
Pattern formation samples. Reaction-diffusion behavior changes according to density field and vector field maps.
ridors” connecting the halls. To achieve this, reefs and empty spaces are associated to the distribution-fields of the morphogen $v$ and $u$ respectively: the result is a cluster of halls surrounded by walls and paths aligned with underwater current vectors in order to reduce at once the reef’s overturning effect and the risk of scuba drivers being pushed against the generated walls. Through the reaction-diffusion algorithm simulation a wide range of possible patterns emerge, associated to particular behavioral rules of the agents-systems. Here are some examples of different system behaviors with their related distributions of underwater clustered halls.

By tweaking the simulation parameters it is possible to explore behavior variations within the system domain, achieving a gradient of possible distributions according to project requirements.

**FRACTAL IMPLEMENTATION**

The issue of dealing with the integration with biological marine biodiversity and provide the material substrate for its future development was not addressed by tweaking the system for a particular requirement of a single specie (or a limited group of), rather the intent is to produce a broad range of heterogeneous spatial conditions in order to provide the largest set of opportunities for the local ecological community (this term refers to the complex food web that shares the same environment). It is anyway necessary to endow the generated reefs with qualities present in the material substrate of other marine environments hosting rich biodiversity, the most significant of which is the presence of cavities: they create a natural localized micro-gradient of resources and energies and are used as shelters by both weak and territorial fish species.

The basic principle adopted is the same conditional void-matter separation based on reaction-diffusion algorithms: the process described above is iterated at a more detailed scale in a self-similarity logic analogous to those governing fractals. Since the Gray-Scott algorithm doesn’t allow a wide range of scale variation over a given voxel matrix, the 3-dimensional pattern obtained so far was scaled using an algorithm based on tricubic interpolation, which allowed the achievement of the desired void pattern scale with a good approximation quality. The result is a scalable and multi-layered domain, where every layer represents a field affecting hierarchically dependent layers, coherently driving formation at different scales. In this model matter, information and processes are scalable.

**Figure 5**

Examples of layouts generated with different ecosystem settings.
CONCLUSIONS

The project provides a material substrate for cultural development and aims to the possible repopulation of local sea-bed by enhancing a pattern of differentiated spaces through the application of morphogenetic strategies that proactively shape the new environment interacting with its own physical characteristics. Although some tests were carried on about underwater behavior of D-Shape material artifacts with positive results, no current testing can provide a reliable trend of its reactions dynamics over time (for instance, resistance to erosion), since large-scale 3D printing technology (such as D-Shape) is still a breakthrough sector in an early development stage and rapid evolution and such kind of tests require a longer timespan to be trustworthy.

However, this shouldn't be an excuse for limiting design speculations, while reasonable constraints that can be found during further extensive testing should instead be considered and embedded in the project strategy. Under the design process point of view, this was a good chance to create a more intimate relationship between morphogenetic strategy and simulated environment. Through finite elements discretization of environment and design object it was possible to develop a solver that through structural and fluid-dynamics based inputs can elaborate a convergent reaction-diffusion configuration based on the designer's parameters. As continuous assessment and rapid adaptation are an intrinsic part of the design approach, further implementation are also foreseen (such as, material behavior and its in-
fluences in terms of weight, mechanical and viscous behaviors over time, erosion). Another reason that limited the physical testing phase has been the lack of investors, although recent contacts with local institutions interested in touristic development and environmental care may provide in the near future the necessary economic fuel to start building a positive network among tourism, culture, material practice and sound environmental transformation.

REFERENCES


