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EMERGENT REEFS

ABSTRACT

The Emergent Reefs project draws on the potential that emerges from a coherent utilization of the environment's inherent ecological structure for its own transformation and evolution, using an approach based on digitally simulated ecosystems and sparked by the possibilities and potential of large-scale 3D printing technology. Considering tourism as an inevitable vector of environmental change, the project aims to direct its potential and economic resources toward a positive transformation, providing a material substrate for the human-marine ecosystem integration with the realization of spaces for an underwater sculpture exhibition. Such structures will also provide a pattern of cavities which, expanding the gradient of microenvironmental conditions, break the existing homogeneity in favor of systemic heterogeneity, providing the spatial and material preconditions for the repopulation of marine biodiversity.

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 nonisotropic three-dimensional field, and integration with the large-scale 3D printing fabrication system patented by D-Shape®.

Out of these assumptions, and with the intention of exploiting the expressive and tectonic potential of such technology, the project has been tackled exploring voxel-based generative strategies. Working with a discrete lattice eases the simulation of complex systems and processes across multiple scales (including nonlinear simulations such as computational fluid dynamics), starting from local interactions using, for instance, algorithms based on cellular automata, which then can be translated directly to the physical production system. The purpose of Emergent Reefs is to establish, through strategies based on computational design tools and machine-based fabrication, seamless relationships between three different aspects of the architectural process: generation, simulation, and construction, which in the case of the used technology can be specified as guided growth.

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1 INTRODUCTION

Coastal erosion is a process that, if uncontested, over time leads to seabed desertification and waterfront thinning. It involves both marine environments and tourism. Italian shores are a typical example: in the past decades, the increased number of tourists has both propelled the economy and increased seabed use and smoothing, thus easing the action of gradual erosion. Much as the intensification of agriculture has led to monocultures and the gradual loss of diversity, the intensification of coastal use in Italy is putting marine biodiversity at risk in favor of human activities through a progressive homogenization of seabed condition. Tourism cannot, then, be separated from environmental issues: tourists are not spectators of a past history or a static vision of a supposed ideal natural condition. Tourism is a proactive vector of change acting within an ecosystem, causing regionally differentiated developments and transformations. Such transformations, often led by a prevalently economic self-sustaining push, are in most cases of two kinds: rapid development of human infrastructures with heavy environmental impact, or strategies that consistently limit economic potential in favor of preserving a static vision of the existing ecosystems. Steering clear of preservationist strategies (which would limit tourism's potential by negatively impacting its economic benefits), tourism must be considered as a part of the ecosystem and a chance for ecosystems to evolve and improve. Tourism must be considered not as a superficial or invasive overlay of functions and uses on a site, and not as a nostalgic postulation of an idealized historical moment, but rather as a positive projection engendering new opportunities for the future. Rather than fetishizing flows of capital and production as a formal device, the project affirms this touristic mode through active intervention with material practices as a substrate to culture. The task then is not to resist the global push of tourism but to seek out the most creative ways to develop richer, differentiated regions within its context. The possibilities of this work emerge from a coherent utilization of the inherent ecological structure for its own transformation and evolution. Considering tourism as internal to the ecosystem also includes evolved functional programs, morphogenetic strategies, and production technologies as efficiently connected nodes of a coherent yet differentiated network. Instead of focusing on the solution of a specific problem—coastal erosion—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 seabed. 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 nonisotropic three-dimensional field, and seamless integration with the fabrication system patented by D-Shape®.

2 D-SHAPE

The entire project was developed with a specific fabrication technology in mind: D-Shape®. This patented technology solidifies sand through liquid infiltration distributed via a custom-built large-scale 3D printing machine. Extending and scaling up the more common 3D printing process, it uses the same additive tomographic layering strategy, with sequential layers of dolomitic sand upon which a row of nozzles drops a patented binder liquid only in the corresponding section points. The initial purpose of the invention was to print houses; however, due to difficulties encountered during the development coupled with the necessity to support the project financially, many different applications have been tried, 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 also the principle that links digital processes to the materiality, applied in an extensive way: two different models of rationality are overlaid with a brute-force method, but one



figure 1

figure 1
Large-scale 3D-printed building components made with D-Shape technology.

lacks geometry generation and the other misses the link to material production. Moreover, as a consequence of this double gap, since the resolution achievable at the moment is quite coarse—the technology is in constant development, with the vertical resolution z direction, the layer thickness, at 5–10 mm so far, and the liquid expansion causes a slightly larger horizontal xy resolution—the emerging pattern is mostly treated as an imperfection, considering the look of the digital model as a result to aim for (Figure 1).

Starting from these assumptions and with the intent of exploiting the expressive and tectonic potential of large-scale 3D printing technology, the project has been tackled exploring voxel-based generative strategies. Working with a discrete lattice eases the simulation of complex systems and processes (including nonlinear simulations such as computational fluid dynamics) starting from local interactions using, for instance, algorithms based on 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. There are several advantages of 3D printing with respect to current technologies for reef restoration and design such as Reef Balls, or experimental precedents such as Biorock®: the possibility of embedding intensive processes in form generation without depending on modular construction (which allows the implementation of a greater specificity and a wider spectrum of heterogeneous spatial conditions, broadening design freedom), while the material system production (it is synthetic rock, not concrete) and integration with design produces large-scale artifacts that allow the implementation of passive strategies for marine repopulation without continuous energy consumption.

The following steps are sorted by process scale, from the broad-space articulation to the generation of void and structure. This order of discussion is solely for the purpose of clarity in explaining the process: the steps were developed at different times and not in the same order, often working in parallel across multiple scales.

figure 2

Synthetic ecosystem screenshot. Written in Processing.

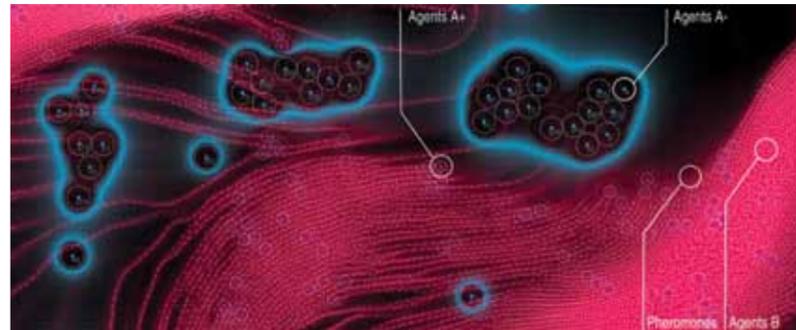


figure 2

3 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, the strategy is based on the interaction with a 3D data field (provided by the simulation of underwater currents) and attractors; in complex adaptive systems, attractors are points in the space of possible configurations of a system (phase space) representing stable configurations, whether static or dynamic, toward which the system tends, generating stable, oscillating, or propagative behaviors. Attractors are used in this simulation to represent the halls as stable configurations and to 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 the charges 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:

$$\phi_A = \sum \pm P_i / R_i^2$$

where ϕ_A is the density at a specified point A, P_i is the charge intensity of the i th 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 cutoff condition for higher values in order to achieve the craterlike configuration of the halls system:

$$\phi_A = 1 - (\phi_A - 1)$$

Exploiting the advantage of working coherently with a voxelized lattice, a computational fluid dynamics (CFD) simulation of the underwater currents is used in order to create a data-permeated space through OpenFOAM® (an open source software for CFD analysis). The data from the speed vectors calculated in OpenFOAM® is read into Processing (thanks to a custom-written import-export plug-in); the vector field is then altered by attractors bearing the same properties as the one described above, causing directional 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 generation and placement of attractors.

4 THE ECOSYSTEM

The adopted morphogenetic strategy for attractors consists of a virtual ecosystem (Figure 2): while interacting with an underwater environment and simulating distribution patterns, it is possible to stumble upon inefficient configurations with low or undesired capacity of nutrient distribution. It is

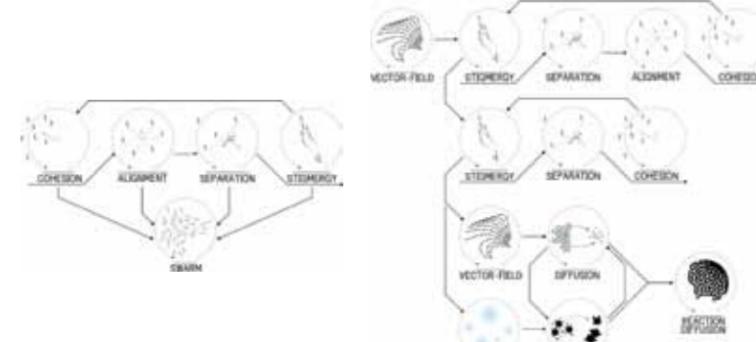


figure 3

figure 4

figure 3

Swarm behavior diagram for B-type agents.

figure 4

Relationship diagram among algorithm steps.

therefore necessary to develop a morphogenetic strategy that, 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 then searches global system coherence as an emergent property of the interactions among the agents in the ecosystem, or, in other words, as the moment in which the global system reaches and maintains homeostasis.

In order to assess the nutrient distribution capacity of the system over time, a simple transportation algorithm is adopted, with the ability to visualize concentration patterns according to vector 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 through a stigmergy-based relationship (Figure 3).

The interaction between the two species does not occur directly, then, but through information released in the environment: nutrients released by B-type agents are stored in the voxel cell corresponding to the agent position and are subsequently transported through the fluid following the currents (vector field directions). Each B-type agent is able to detect nutrient concentration and moves in search of higher concentration areas. This evaluation is achieved through the analysis of neighbor cells that return the gradient of density function:

$$v_D = c_s \cdot \nabla D = \partial f / \partial x \cdot i + \partial f / \partial y \cdot j$$

where v_D is the movement vector related to density function D , and c_s is a coefficient of sensitivity to 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 (Figure 4).

A type agent class is subdivided into two subclasses, determined by the sign of c_s coefficient and correspondingly different behaviors: A- (generative behavior) and A+ (dissipative behavior). A- agents search for areas where nutrient concentration is minimum and generate a magnetic-like field (such as those described previously, with inverse-square distance propagation rule) that varies in extension and magnitude according to number and charge of clustering agents; while A+ agents search for areas where nutrient concentration is maximum and can dissipate a 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's 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. The 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.

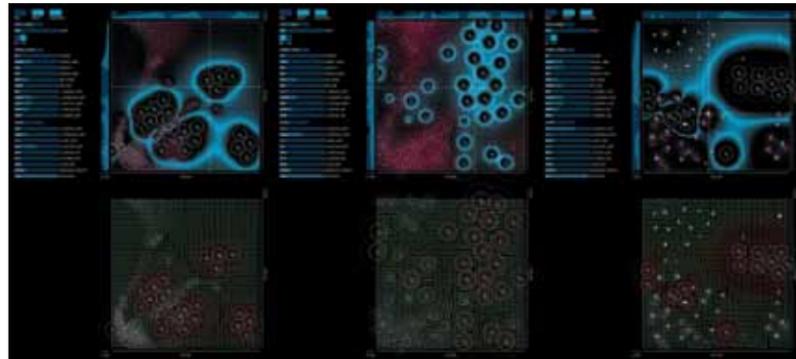


figure 5

The simulation can be stopped manually when the ecosystem reaches a stationary condition (Figure 5); 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 is also possible to 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.

5 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 reef's 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 Turing, 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, generating differentiation patterns that can account for processes such as brain growth and its spatial articulation or the pigmentation of animal skin. The reaction-diffusion process is implemented using continuous cellular automata algorithms over the 3D voxel grid, which is the same underlying structure that allows a seamless transition through all the steps of the overall process, from analysis to fabrication. Voxels in the grid act like buckets where any kind of data relative to that sector of space can be stored. Every 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 neighbors. The remaining 20 cells, with only an edge or a vertex in common, are used to cover a wider range of possible behaviors, also implementing 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:

$$\phi/\partial t = D \cdot \nabla^2 \phi$$

where:

- ϕ is the concentration in dimensions of [(amount of substances)·L⁻³]
- t is time [T]
- D is the diffusion coefficient in dimensions of [L²·T⁻¹]

figure 5

Examples of different field configurations emerging from variations in the agents' behavior.

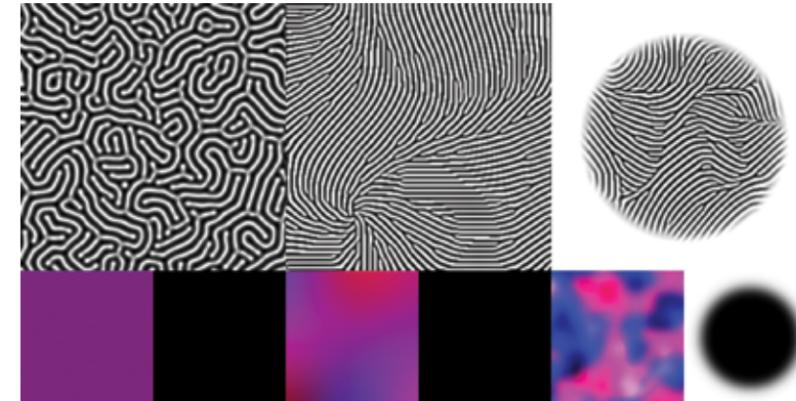


figure 6

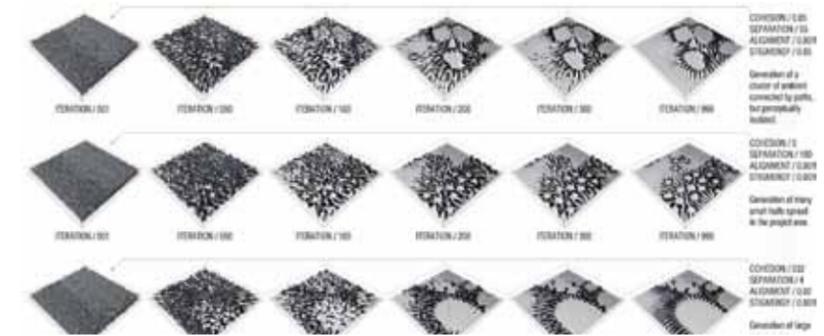


figure 8

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:

$$\begin{aligned} \partial u/\partial t &= D_u \cdot \nabla^2 u - u \cdot v^2 + F \cdot (1 - u) \\ \partial v/\partial t &= D_v \cdot \nabla^2 v + u \cdot v^2 - (F + k) \cdot v \end{aligned}$$

where $\partial u/\partial t = D_u \cdot \nabla^2 u$ and $\partial v/\partial t = D_v \cdot \nabla^2 v$ represent Fick's second law of diffusion: Du and Dv are the diffusion coefficients of morphogens u and v respectively, with Dv < Du.

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 (Figure 6). The term density refers 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, thus coherently exploring variation at the present system scale.

6 LAYOUT PATTERN

The importance of anisotropy in pattern distribution arises from several necessities: to avoid reef overturning; to coordinate scuba divers' trajectories and underwater currents with the reef formation itself in order to minimize the chances of human-reef collision (cross-directed currents would push

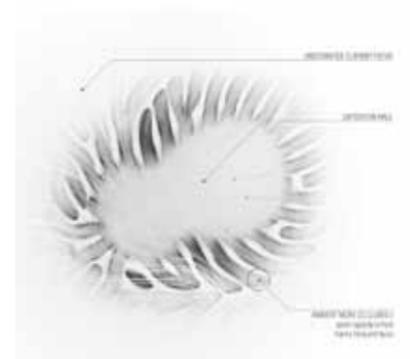


figure 7

figure 6

Pattern formation samples. The behavior of reaction-diffusion changes according to the density field and vector field maps. Blue channel intensity corresponds to vector x-component, while red represents y-component.

figure 8

Examples of layout generated with different ecosystem settings.

figure 7

CFD analysis of a chosen hall from a generated layout.

figure 9

Voxelized space allows a direct multiscale implementation of 3D structure in large-scale fabrication using D-Shape® technology.

figure 10

Gray-Scott algorithm applied to a frame of final layout.

figure 11

Side views of fully developed reefs with scale reference.

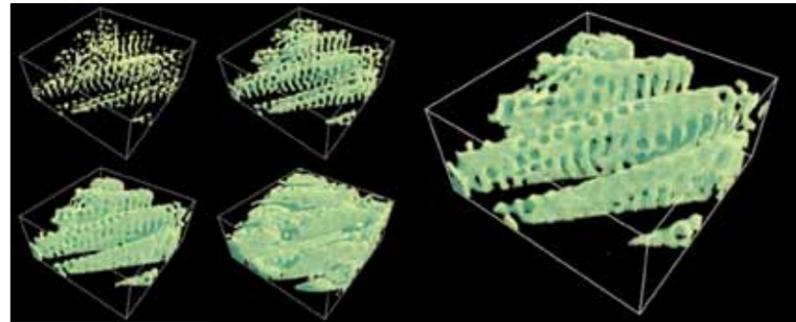


figure 9

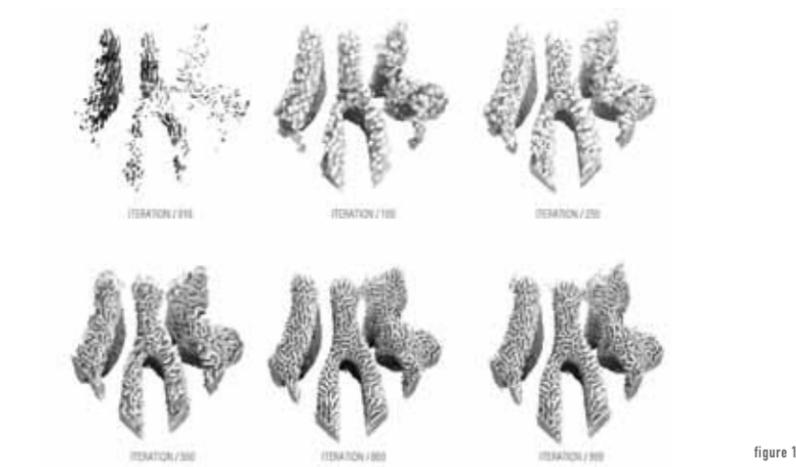


figure 10



figure 11

divers against the reefs); and to provide a distribution system of “corridors” connecting the halls. To achieve this, reefs are associated with the distribution field of the morphogen v : the result is a cluster of halls surrounded by series of walls and paths aligned with underwater current vectors in order to reduce both the reef’s overturning effect and the risk of drivers being pushed against the generated walls. Through the simulation of the reaction-diffusion algorithm a wide range of possible patterns emerge, associated with particular behavioral rules of the agent systems (Figure 7). These 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.

7 FRACTAL IMPLEMENTATION

Regarding the issue of marine biodiversity and providing the material substrate for its future development, the system was not tweaked to meet the particular requirements of a single species or a limited group of species. 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—the complex web that shares the same environment (Figure 8).

It is, in any case, 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 microgradient of resources and energies and are used as shelters by both weak and territorial fish species.

figure 12

SLS prototype of resulting nested reaction-diffusion.

figure 13

Underwater view.

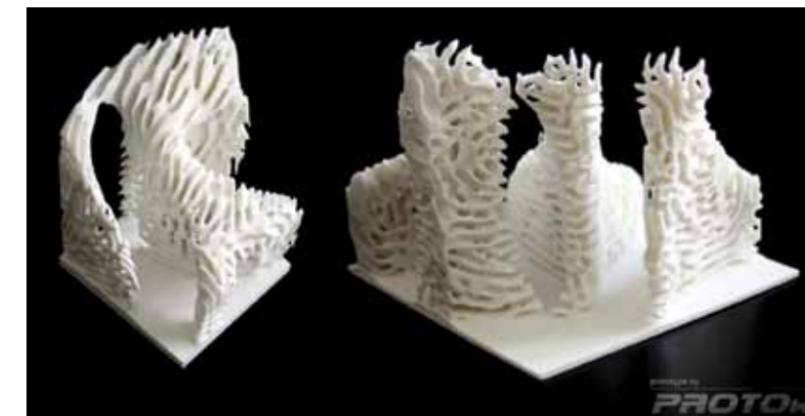


figure 12



figure 13

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 (Figure 9).

Since the Gray-Scott algorithm does not allow a wide range of scale variation over a given voxel matrix, the three-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 good approximation quality. The result is a multilayered domain, where every layer represents a particular field. In this model material system distribution, information and processes are all scalable: the process is iterated with systemic yet heterogeneous results at different scales (Figures 10, 11, and 12).

6 CONCLUSIONS

The project provides a material substrate for cultural development and aims at the possible repopulation of local seabed biodiversity by enhancing a pattern of differentiated spaces through the application of morphogenetic strategies that proactively shape the new environment through interacting with its own physical characteristics (Figure 13).

Although some tests were carried out of underwater behavior of D-Shape material artifacts with positive results, no current testing can yet provide a reliable assessment of its reaction dynamics over time (for instance, resistance to erosion); large-scale 3D printing technology is still a breakthrough sector in an early development and rapid evolution stage, and such tests require a longer timespan to deliver trustworthy assessments. However, this should not be an excuse for limiting design speculations. (Of course, real constraints that may be found during further testing should be taken into account and embedded in the project strategy.) As continuous assessment and rapid adaptation are an intrinsic part of the design approach, further implementation is also foreseen (such as, for instance, material behavior and its influences in terms of weight, mechanical and viscous behaviors over time, erosion, etc.).

Another reason that has 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 the necessary economic fuel to start building a positive network among tourism, culture, material practice, and sound environmental transformation.

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WORK IN PROGRESS

LOW FIDELITY

ABSTRACT

A contemporary exhaustion with technological fidelity (Gow 2011) has identified an environment where control and precision are reduced to illusive promises in the game of materialization. The recent ascent of the homogenous copy, arguably brought on by the onslaught of digital tools, has collapsed the gap between the object and its representation, obliterating the productive tension and creative friction from architectural design methodologies.

This work proposes to reopen the gap and locate new sites for architectural design by engaging in the translational discrepancies that occur through mediums of architectural representation, not as instances of dilemma but as opportunities to subdue tautology and augment the seductive latency of representation (Perez-Gomez and Pelletier 1997). In an attempt to negotiate the digital and physical, this work situates itself within the feedback loop between the translations of architectural ideas, representational strategies, material propensities, and back again. The discrepant becomes a dynamic catalyst through the engagement of participatory tools (Carpo IKKM 2011), interactions with matter, and processes of materialization.

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