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Emergence: Form Finding In Nonlinear Architecture

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Abstract—**Inspired by new scientific theories, many experimental architects have already begun to study how to transfer nonlinear theory into architecture. This essay asks: Is the design process in nonlinear architecture intelligent and smart enough for current digital and information age?**

Keywords-emergence; form finding; process; nonlinear architecture

I. INTRODUCTION

In the 21st century, people desire to understand complexity within society better than the last century. Nevertheless, classical science and modern architecture are linear [1] and easy to analyze, but cannot deal with complicated phenomena that arise directly out of nonlinearity [2], which characterizes our digital and information age. Charles Jencks articulated, "Whether we really do have a new science, one different from the old modern linear sciences which grew from the Newtonian paradigm"? [3] In nonlinear sciences, nature is not a clear cause and effect system, but a sophisticated one. Inspired by new scientific theories such as chaos theory, which studies dynamic systems in nature, many experimental architects have already begun to study how to transfer them into architecture, to explore a new design methodology for studying complex design problems. For architecture, one innovative, smart, and dynamic form finding process is necessary to serve more intricate design requirements better. This essay asks: ***Is the design process in nonlinear architecture intelligent and smart enough for current digital and information age?***

II. RESEARCH METHODOLOGY

The structure of this investigation is bottom-up: three nonlinear systems that Force Field, Swarm Intelligence, and Self-Organization are studied considering their popularity in existing nonlinear architecture; one or two experiments are conducted within findings that engage further questions resulting in a proposed form finding workflow. The objective of the following case studies of nonlinear systems and simulations is to discover what are the weakness and limitations in nonlinear architecture; is a parametric system just a design tool or new theory or methodology; what has been ignored or could not be simulated in computers? Based on this research, the paper concludes with a discussion regarding what we can learn from nonlinear architecture and where it is heading in the future.

III. NONLINEAR SYSTEMS AND SIMULATIONS

1. Force Field

Force field is composed of two concepts: field and force. "Fields are mathematical objects defined over manifolds which enrich them with spatially varying properties". [4] If we take a surface not as an entirety but a swarm by dividing it into a number of equal sub-surfaces, a field appears. We generate fields by way of dividing and subdividing one thing into many matters usually. Force is attraction; through deforming original fields by attractions, designs can achieve an interactive system to affect building systems. A transformable field is defined by two conditions: first, its default property (logics and forms); second, the way forces affect it.

Case Study: Sinosteel International Plaza by MAD
Location: Tianjin, China
Typology: Office/ Hotel/ Service Apartment

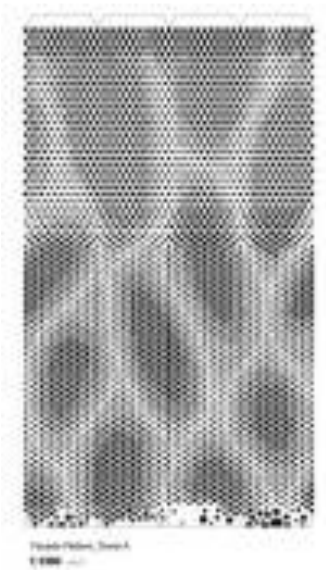

Figure 1. Sinosteel International Plaza
Source: http://www.i-mad.com/index.asp?go/#/projects/all/31/

MAD makes a façade pattern that creates an ever-changing image of the building from different perspectives. Different sizes of hexagonal windows are arranged in an irregular and seemingly organic honeycomb. In function, it is not for aesthetic performance, but for energy efficiency that responds to site climate conditions. By way of ecological analysis in computers, windows are positioned and sized according to energy conservation and natural lighting requirements, to reduce heat loss in winter and heat gain in summer [5]. Pattern follows function and generates aesthetics meanwhile. This project illustrates potentials to achieve sustainability and beauty through integrating digital analysis and parametric controls. Parametric designs are good at controlling building performances. But one problem concerns the use of original hundreds of window sizes. Many window sizes are not feasible considering fabrication difficulty and construction cost. Eventually, only five sizes are chosen as window modules. Sometimes, final construction cannot realize complex parametric design in full perfection since practical limitations.

Experimental Simulation: Dynamic Pattern

The above sample utilizes ecological simulations to control window sizes. I choose another way to explore more possibilities through curve interference. Point and curve interference are two most common methods to affect a vector field. Landscape views for instance, can be parametrical through defining points or curves to interfere building façades. In Fig. 2, I set up four interfering curves to affect hexagons' sizes. Through calculating distances between centers of hexagons and the nearest one curve of that point, the radius of each hexagon is determined. If curves represent the best landscape viewpoints on building facades, then, an algorithm suggests that if the surrounding cells are closer, the larger their openings. In this way, design becomes site-specific and landscape beneficial. On the other hand, we may set more parameters (such as ventilation, heat gain, interior activities) as points, curves, or other kinds of physical or numerical forms simultaneously, to function better and more precisely.

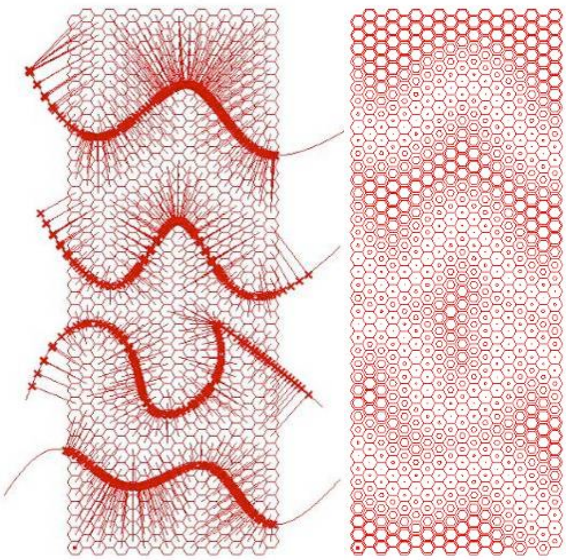

Figure 2. Dynamic Pattern

Source: Author

Case Study: Phoenix Shopping Street by XWG Studio
Location: Beijing, China

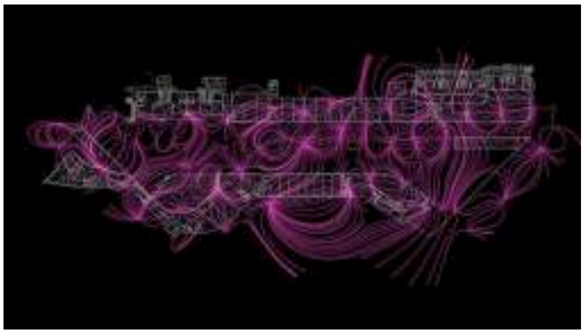

Figure 3. Phoenix Shopping Street

Source:http://xwggzs88.dns32.trtr.cn/(S(5v00ynf32rt0ud450gsm3m45))/Project.aspx?id=108

The design concept is to connect two originally separated commercial streets through an umbrella-like installation. XWG studio creatively holds that commercial landscape spaces are similar as magnetic fields. Driven by magnetic lines of force, diverse functional spaces are woven together organically, and respond to surrounding commercial atmosphere dynamically [6]. Interestingly, each shop is deemed as an interior magnet and architects set a series of magnets in outdoor public spaces. Simulated in computers, magnetic points act and react upon others dynamically according to their magnetic weights. Then, corresponding magnetic lines are generated to define magnets' boundaries. To get three-dimensional forms, the Voronoi [7] algorithm and gravity fields work together to simplify patterns and define centers of gravity for columns' placement.

I argue that the connections between shops and outdoor "umbrellas" are weak, especially for commercial functions. Exterior installations are still isolated from interior spaces. Designers may embed little considerations for practical usages when modeling the parametric system in computers. Functional parameters are harder to set up and define in computers than building forms, but if they are not configured and defined well, the nonlinear system will be only form-oriented and a spatial game. "Ornament should actually be considered as fully operative, or to use their vocabulary, a functional dimension of architecture". [8] Finally, "a field condition could be any formal or spatial matrix capable of unifying diverse elements by intricate local connections, not by overarching geometrical schemas". [9]

2. Swarm Intelligence

Swarm intelligence is a concept that originates from biology:

> *Deals with natural and artificial systems composed the discipline of many individuals that coordinate using decentralized control and self-organization. The discipline focuses on the collective behaviors that result from the local interactions of the individuals with each other and with their environment [10].*

As Delanda points out, "The dynamics of populations of dislocations are very closely related to the population dynamics of very different entities". [11] Zaha Hadid Architects' parametric urban design illustrates quite well how to utilize swarm intelligence to study urban issues.

Case Study: Parametric Urban Design by Zaha Hadid Architects
Project: Kartal Pendik Master Plan
Location: Istanbul, Turkey

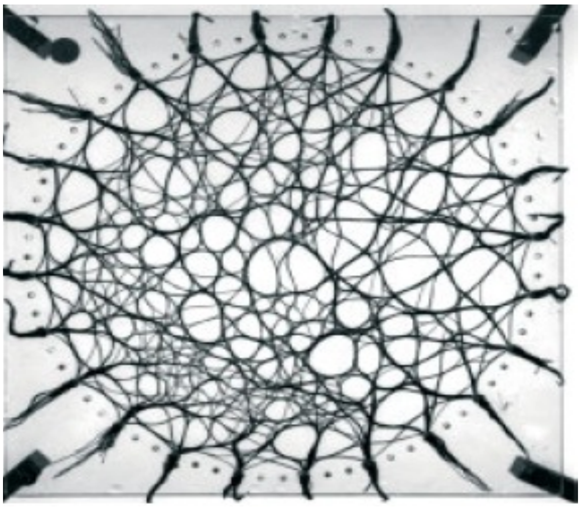

Figure 4. Wool-thread model to Generate Optimized Path Networks

Source: Schumacher, Patrik. Parametricism: A New Global Style of Architecture and Urban Design [12]

Kartal Pendik Master Plan purposes to integrate a couple of transportation systems into an urban complex, to redevelop an abandoned industrial site in Istanbul. Concepts derive from Frei Otto's minimal path system [13]. Frei Otto's form finding process brings a number of systems into a simultaneously self-organizing force field so that any variation in the parametric system will act on each element and then respond to all others. Architects utilize hair dynamic systems in Maya (animation software) to simulate a digital wool-thread model in computers, which share similarities as Otto's research. The set-up registers the multitude of incoming streets and bundles them into larger roads affording larger parcels. Later, a deformed grid merges into the detour network. At the same time, script can determine width and height of blocks depending on parcel size, proportion, and orientations [14].

Patrik Schumacher asserts parametricist urbanism operates via the mutually accentuating correlation of multiple systems: fabric modulation, street systems, and a system of open spaces [15]. An overall urban design succeeds to integrate distinct city systems through defining their parametric relationships and to coordinate these systems into one organic cityscape. This urban design illustrates how to design a functional efficient and sustainable urban area through digital simulations by means of scripting and both mathematical and architectural algorithms.

After appreciating aesthetic elegances in this design, I question, what is missed in parametric urban designs? Perfect swarm intelligence urban designs still have to confront realistic problems: slum areas, downtown revival, and suburban sprawl. Other than that, key points such as citizens' willingness, real estate development, and historic preservation are ignored in this parametric system. To accomplish it, we should realize that digital tools do not manifest sufficient pre-rationalization considerations on constructability or materialization. This weakness exists when digital tools face something that is incomputable or not algorithm-able. Thus, I conceive a simulation that may be useful in urban transportation design to solve complicated problems.

Experimental Simulation: Multi-Agent Systems

Multi-agent systems can simulate flocking behaviors in nature. In this experiment, each point is an agent and the cube is a boundary box that all agents can only move in. Agents start from random positions in this cube with random default velocities. Then, they head forward along a direction to new locations as time goes by. I define maximum velocity of all agents and their steering forces, which act upon others. Influential forces can be repulsed when two agents are too close or become attracted. This depends on how far away they are from each other. Steering forces will exert acceleration (positive or negative) on the original velocity of the target agent. Thus, an agent will speed up when there are few neighbors and slow down when it meets others.

The amount of agents, time of duration, starting locations of agents, and some parameters about velocity and steering forces are adjustable in the algorithm. When the quantity of agents and duration time are large enough, observers can trace orders from the chaotically dynamic process because some agents behave similarly.

How can this study help us design smartly? Swarm intelligence is helpful if used to assist urban designs, especially transport systems. Each agent can be a vehicle, a bike, or a man with certain velocity and heading direction. When we put many agents together into an urban area (two-dimensional), they will run as cars and people in reality and exhibit routes that are more popular or scarcely used. Besides, in three-dimensional spaces, this flocking system is valuable to design vertical transportations in large-scale buildings like skyscrapers.

3. Self-Organization or Self-Adaptation Systems

Self-organization [16] or self-adaptation [17] system is a real-time responsive system in nature. Similar as swarm intelligence, the whole entity consists of a number of agents. Each agent will mutate according to changes in exterior environment, and this mutation usually follows certain rules. In the end, a new 'whole' will emerge based on individual agents' mutations. "It is useful to think of an agent's behavior determined by a collection of rules". [18]

Case Study: Material Transformation Research in AADRL (Architectural Association's Design Research Lab)

Team Names: Ahmed Abouelkheir, Ji-Ah Lee, Behdad Shahi, Junyi Wang

Tutors: Yusuke Obuchi, Rob Stuart-Smith

This experiment records and shows the transformation process of material self-organization. Inspired by dunes in desert and considering its fluidity, sand is main material to find organic forms. Several holes are made in the box bottom in advance, then, pour enough sand into box containers. Sand flows and drops into lower containers attracted by gravity and transformation process slows down gradually since friction among particles. Then, organic cone-like forms will shape [19].

"As loose accumulations of vast amount of separate particles, aggregates form as dynamic equilibrium patterns under the influence of extrinsic influences, such as gravity and wind, dead weight and internal friction resistances". [20]

Natural forces, not designers, drive this form finding process. The part-to-whole system works as each agent acting on surrounding particles by way of friction. Researchers suppose, "These natural resources could be a part of a tectonic system to create an architecture that changes continuously". [21] However, this study inspires me to find a form, which is environmental responsive, self-organized, self-supportive, and within smooth transitions of patterns and edges between secondary spaces. One problem which intrigues my thinking is most construction materials are not as fluid as sand. Architecture needs new materials, transformable ones, even smart materials that respond to exterior changes through form transformation.

Experimental Simulation: Dune

I simulate the same process discussed above via a physical way. Locations of openings influence the final shape or pattern. If holes are dense in one area, these cone-like shapes will be smaller, denser, and slopes will be steeper. In Fig. 5, contours of dunes are not circular and the number of edges depends on how many neighbors each dunes has. Thus, locations of holes are decisive parameters for final forms.

Figure 5. Physical Simulation

Source: Author

In a corresponding digital simulation, one dynamic system is modeled in parametric software to accomplish seven forms via changing numbers and locations of holes. The pattern of dunes is similar as that one of points. Designers merely need to modify locations of points to control the system.

Case Study: Cellular Automata - Behavioral Urbanism

Architects: Robert Stuart-Smith, Diego Perez, Yiota Goutsou

"Cellular automata are discrete models of regular grids of cells each one in a finite number of states that update based on the values of their neighbors". [22] Designers set up basic rules for this system and it will evolve automatically, and an increasingly complex whole will appear as self-referential result. This design by AADRL proposes a mix-use housing area in Shanghai, China. Cellular automata generate a differentiated built environment to deal with the interrelations between spaces and forms. The bottom-up process emerges nonlinear spatial orders inside the site and creates complexity and unpredictability in different urbanisms [23].

It explores the way to treat and consider complex urban issues, especially for modern cities' high-density living areas. Cellular automata start from behavior of each single cell, use functional rules to organize individuals and aims to achieve an interiorly and exteriorly interactive urban complex. That would be amazing and functional if visual connectivity, orientation, ventilation, and landscape are all parametrical to drive the growth-up process.

Experimental Simulation: Self-Growthing

Cellular automata-Conway's game of life rules (developed by "MORPHOCODE" design ground), is my test algorithm to generate forms. Each cell exists in one of two possible statuses: dead (unseen) or alive (seen). These inputs may be altered:

1. Time, how many steps are necessary for the form to evolve;

2. Neighbors, how many live neighbors can keep a living cell remain alive or to die because of loneliness or overcrowded conditions, or dead cells come to life when surrounded by certain number of individuals;

3. Boundary, a grid contains all cells and limits the space the form may evolve;

4. Points that initial state of a set of cells that are primitive alive ones [24].

After defining all parameters and triggering the time controller, the original cubes will evolve systematically in three-dimensional ways. Each time, I change one parameter separately in order to understand its influence overall. The form grows up gradually with time goes by; it evolves from bottom to up, floor by floor, and inward to outward.

Evolutionary rules are essential. Amount of cells decreases heavily when demanded living ones augments. More required living neighbors of a dead cell restrains its possibility to be alive. Consequently, rules of dead cells control the quantity and density of cubes, looser conditions generates more individuals.

For living cells, the amount of cells has no direct connection with the number of required living neighbors. Rules influence the shape of a form (centralized or spread out), not the number of cells. In architecture, is it possible to control forms by correlating this role to architectural qualities, such as day lighting, ventilation, and landscape views? When these questions are solved, a living cell is about to be a livable cell.

Initial state is the number and locations of original living cells. Decentralized status is more likely to generate detached towers, and when initial individuals are too far away, the system may fail or towers are totally separated. In building and urban designs, this parameter is helpful since it can be defined according to site conditions, to emerge a centralized organism or several individuals that are only partially attached.

Utilizing cellular automata in architecture is a promising way considering its benefits to the equality of living suites, especially for high-density residential buildings, crowded urban areas, or developing countries, where enormous amount people live. However, cellular automata are still too simple to mimic a real world and not easy to control as their invisibility and unpredictability. A cellular automaton system will generate some unusable spaces and cells, which have to be removed. Last, some practical issues, such as vertical transportation, mechanical facilities, and emergent egress, are all difficulties when designs need come to true.

IV. FORM FINDING PROCESS WORKFLOW

Based on above case studies and simulations, I propose a form finding workflow in nonlinear architecture.

1. Parameters information gathering: before modeling a parametric model in computers, architects determine what needs be set up as parameters and how to digitize these design information into parametric models. Data can be either static or dynamic. Dynamic data are preferable considering its possibility to unearth dynamic relationships among parameters.

2. Parametric modeling or system design: to make one or several algorithms to connect and control all parameters is the crux of the matter. Algorithms erect dynamic relationships among parameters, and simultaneously get feedback when one parameter changes. The complexity, intelligence, and usability of a parametric system determine building performances.

3. Feedback and modification: After finishing first two steps, a series of primitive building forms will emerge. Here, one building form is only an embryo, not a final one. The form is merely one temporary feedback from the parametric system under certain parameters. If we change the input data, the system will output a new form, which could be quite different from the previous one. In order to find out the best or at least an appropriate form, designers have to change the sorts and values of parameters many times, or even abandon the original parametric system and model a new one. Emerging-to-modification is a dynamic and reciprocal process, which never stops until design finalization.

4. Fabrication and construction preparation: Nonlinear architectural forms are usually irregular, dynamic, and complex. Conventional on-site construction strategy may not meet design requirements. Therefore, off-site fabrication through digital control machines, such as CNC (Computer Numerical Control) milling, is very common in practices. Although fabrication can be the last part in a design process, if considered in previous steps that will save time and cost much. Dimension, material property, fabrication machines, budget, and construction techniques are all factors that should be premeditated, even, are set up as parameters in previous steps.

WHAT CAN WE LEARN FROM NONLINEAR ARCHITECTURE?

If designers use the form finding process unintelligently, they will get lost in the form-and-function debates or architecture - nonarchitecture critiques. To be a mature design methodology, nonlinear architecture should follow basic principles. At present, two theorists' opinions may be helpful. John Holland states that,

1. *Rules that are almost absurdly simple can generate coherent, emergent phenomena.*

2. *Emergence centers on interactions that are more than a summing of independent activities.*

3. *Persistent emergent phenomena can serve as components of more complex emergent phenomena [25].*

Patrik Schumacher offers, "Parametricism implies that all architectural elements and complexes are parametrically malleable". [26] This manifesto is bold but disputable that how many and what kind of architectural elements can be parametrical. For spiritual and political elements in architecture, I have not found any superiority in nonlinearity compared with conventional design methodologies. His conclusion has two parts:

Formal heuristics

Negative principles (taboos):

avoid rigid forms (lack of malleability)
avoid simple repetition (lack of variety)
avoid collage of isolated, unrelated elements (lack of order)

Positive principles (dogmas):

all forms must be soft (intelligent: deformation = information)
all systems must be differentiated (gradients)
all systems must be interdependent (correlations)

Functional heuristics

Negative principles (taboos):

avoid rigid functional stereotypes
avoid segregative functional zoning

Positive principles (dogmas):

all functions are parametric activity/event scenarios
all activities/events communicate with each other [27]

Schumacher's proposal of rules for a new style is strong and exposes the essence in nonlinear architecture: dynamic and malleable forms are more valuable than rigid forms; rigid forms are appreciable only in the case that they are embedded enough complexity and adaptability. Complexity in nonlinear architecture mostly exists in building systems. We hope all building systems are parametrical and not be isolated; they influence and are woven into each other.

Another issue is how to deal with the relationship between digital techniques and nonlinear architecture? I address that architects need use digital software intelligently, as computeraided design. Using computers compute for us, not just to draw. One more question is who will control the design, architects or computers? I agree with Roland Snooks' statement,

The algorithm should emerge from an architectural problem rather than architecture emerging from algorithm. ... Algorithms often work in a deterministic way and often that does not have the sophistication to enable you to embed any architectural concern in it [28].

Algorithms are just tools to figure out certain design problems. They are not omnipotent. Meanwhile, algorithms may generate new problems, especially when they are devoid of material and scale considerations. It is not the intelligence of an algorithm, but how smartly designers use it that determines design qualities.

V. Conclusion

This essay provides general understandings of form finding process in nonlinear architecture. Some issues can be discussed further, such as which system is more appropriate to design building forms not transportation spaces. One difficulty is merging several form finding methods into one building design. At present, samples about such work are rarely conducted and can be a future topic too.

Nonlinear architecture allures and evokes architects to rethink the essence of architectural design and human future. As Charles Jencks states,

Is the new nonlinear architecture somehow superior, closer to nature and our understanding of the cosmos, than old modernism? Is it more sensuous, functional, liveable? Is it closer to aesthetic codes, which are built into perception? Has it supplanted the traditions from which it has grown—Post-Modern and Deconstructivist architecture? [29]

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