Biomimetic nanotechnology and nonlinear dynamics

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Abstract

The biological approach to nanotechnology – biomimetic nanotechnology- is a new field in the area of nanostructuring and specially nonorobotic. Mimicking biology to extract useful strategies, needs good knowledge of its exquisite dynamic (evolutionary nonlinear dynamic) which arises from a vast network of molecular interactions and structure-function hierarchical solidity from small scales (nano) to large scales (macro).

In this sense the identification of self-assembly processes in living systems and their self-organized dynamical states with the knowledge about their sensitivity and selectivity have paved the way for developing new strategies for controlling the dynamic of self-assembled structures in nanoscale. Hence by mimicking the way in which biological structural components are built, the process of pattern formation or self-assembly can be directed in a desired form.

1. Introduction

Nanotechnology is the construction, generation and growth of objects, devices and architectures at the nanometer scale (10^9) which is the world of brownian motion and atomic interaction and uncertainty.

Nano is the atomic, molecular scale. All things around us are special configurations of molecules, but among all of the possible formations, only a few percent of them are known yet. Nano has great advantages which motivates us to minimize technology size. For example, big deals about nanomaterials are that they display high surface area, have high surface energy, can be more reactive and catalytic and can have different physical and chemical characteristics.

Today the ambitious goal of nanotechnology is construction of a machine which can arbitrary select and organize molecules in a way that a control of structure can be achieved; In other words, "constructing a molecular assembly or a machine that can direct molecules in a proper formation".

There are two strategies for nanotechnology [3]:

1- Mechanistic version: in which, the material world is completely atomized due to the notion of the aggregation of particles. From this point of view, it may be possible to create every thing in a desired form by arranging atoms and molecules properly. The basic idea in this way is to assemble precise intricate structures by bringing molecular together using direct mechanical control. That is to make things by putting their elementary parts where they should be. But grabbing a molecule or molecular structure and move it, or hold it in a precise location is not easy to deal with.

2- Biologically inspired and biomimicry version: In this way, instead of mechanically arranging the atoms, biomimetic technology aims to mimic the functionality of existing biological systems (such as DNA, protein and cell). For instance, if two complementary strands of DNA are left to drift around in an appropriate solution for long enough, grasp together in a double helix. Also a protein, a one dimensional strand of amino acids, will wiggle around for a while and then eventually curl up into a 3D structure that is determined by its 1D amino acid sequence. The strategy in this way is to harness such naturally self assembling processes.

However in both cases the control of nanoparticles is crucial: in mechanistic nanotechnology, controlling the wild brownian interactions of atoms and molecules to create stable and functional objects, and in biomimetic nanotechnology the precise control of biological system and their assembling processes in order to achieve the desired output. In other words, architectured nanosystems must exert tight control over molecular motion and their binding. They must exclude unwanted molecular encounters while ensuring that desired interactions occur with a proper accuracy.

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In this paper we will focus on biomimetic nanotechnology and the essential control process of its phenomena in order to explain the possibility of achieving functional and organized materials, devices and structures. But first, a brief introduction to biomimicry is mentioned.

2. Biomimicry

Above the physical aspects of nano-micro assemblers, the synergy of nano and bio is a turning point in which the nanoscale machines take its inspiration from and also actively utilizes existing biological systems. A particular interesting feature of nanoscale is the scale on which biological systems build their structural components [2]. As mentioned previously, biomimetic nanotechnology is concerned about biologically approaches to nanotechnology in order to produce self-assembled architectures. Remember that in biomimetic science or biomimicry, the idea is to mimic functional properties of biological components or the process by which they are manufactured in nature to achieve new superior properties or manufacturing advantages. Biology has intrinsic characteristics which helps us to create systems in smaller scales. Some of these characteristics are:

Selectivity and sensitivity in a scale of a few atoms, capability of individual units to produce themselves in a mass and with an infinitesimal error, self assembly in complex systems, the ability of function and form compatibility, the ability of damage detection, self repairing and strongly interacting and communicating particles.

It is obvious that in emulating biology, there are multiple levels of biomimicry as biological functions of an organism, clearly are designed based on a hierarchy of size scale. It seen that simple atoms and molecules at nanoscale are combined to make complex structures, such as DNA. In microscale, cells like neuron and glia interact to make higher phenomenon as memory, emotion and thought, and at the organism level, multiple physical and chemical processes with cognition unit combine together to produce life and human emergent characteristics. Of course at the most fundamental level, function and structure necessary for life, result from factors as specific molecular shapes (antibody and enzyme binding sites), DNA interactions, cell-receptor recognition, cell transport and communication and cell-cell recognition. In fact most fabrication processes in wide use today, operates on molecular self assembly and relay on selective interactions between molecules to produce fully ordered supramolecular products. Also, most of the successful self assembled nanostructures are made by DNA. Hence we will be more concentrated on this scale and its characteristics. In this view, naturally occuring molecular self-assemblers such as protein and DNA, represent a functional equivalent of self-assembly and self-organizing molecular machines. Thereby it seems that by engineering DNA on a molecular level, machines out of atoms can be built and then programmed to build more machines and so on (nanotechnology).

After introducing the necessity of biomimicry for nanostructures and nanotechnology, these questions may appear, how this process can be done and what are the essential tools for it? Or the question as, how the crystallization, formation or growth processes can be controlled?

3- Processing (engineering) tools

As became evident in last section, for developing nanostructures, emulating the biological behavior at nanoscale is helpful, because biological nanostructures, via molecular Self-assembling and templating of atomic and molecular structures, are formed. Mimicking this feature in artificial self-assembly process, molecular building blocks must be designed to fit together in only a desired way and also these building blocks must encode the structure of the ultimate product themselves. Only in this way -by controlling of brownian motions and nonlinear interactions- intricate machines can assemble.

However before doing such an engineering process, we must know exactly the features of biological self-assembly. As mentioned in [1], self-assembly in biological systems has four distinct characteristics:

1) Programmed (coded): self-assembly in living systems is based on information encoded into the components themselves. Besides the coded instructions, the features of environment determin the outcome of self-assembly in living systems.

2) Constrained (templated) self-assembly: order and asymmetry in self-assembled aggregates of biological molecules are often achieved by imposing constraints. These constraints may be found in biology or imposed from environment.

3) Hierarchical self assembly: the organization of biological structures is integrated across length scales from molecules to the organism level, (i.e. hierarchical self-assembly from building blocks –molecules- into the complex structures).

4) Dynamic self-assembly: biological processes are mainly dynamic, i.e. they exist out of equilibrium and these systems maintain their characteristics order only while dissipating energy.

In analogy to these natural characteristics, the shape and functionality of artificial self-assembled aggregates

are governed by the shapes of their components, by the interactions between them and by the environment constraints imposed on them [1]. Generally the artificial self-assembly can be categorized into two main classes of engineering processes; first, synthesising of the appropriate building blocks and second, controlling the building blocks self assembly process. Synthesising appropriate building blocks and then defining proper set of particles can assemble to perform desired operations and define patterns with much greater complexity than their total number. Also the control process of these building blocks is a product of a repetition of force for controlling the growth (formation) in a desired way. Control over the structure and thereby the properties of self-assembled aggregates have been achieved in several ways by borrowing strategies from biology.

For instance, crystal structure design is a special case of atomically precise molecular self-assembly. Striking examples of precise self-assembly have been produced through the design and fabrication of branched double strand DNA structures. These structures have been used to implement simple molecular machine and have been proposed as a means for organizing active component in molecular system. The design methodology for these structures uses computational methods to identify DNA sequences in which bases will pair to link particular strand segments while minimizing unwanted pairing between another segments (control process). We will discuss more on control process in the following but first, general characteristics of biomimicry tools are mentioned.

As suggested by [5] for mimicking the evolutionary behavior of biosystems and their special features, such as self-organization and selection, some evolutionary computations are needed. It means that mean field theories and preprogrammed softwares and information processing techniques are inadequate since they are only syntactic and are not suitable for special dynamic of biosystems in which, structure- function hierarchical solidity from small scales (nano) to large scales (macro) exist. This feature of biosystems, inseparable structure – function (software – hardware) solidary wholeness, has some appearance in behavior as:

Autonomy, multifunctionality, compactness, compatibility, self-replicating, hierarchical self-organizing, stability vs. compatibility and flexibility vs. stiffness.

This holistic characteristic arises from the nonlinear dynamic of biological complex adaptive system. This rich dynamic (evolutionary nonlinear dynamic) is a result of a vast network of molecular interactions involving a high degree of nonlinearity and is due to the system characteristics as they are open and far from thermodynamic equilibrium. They are continuously exchange matter, energy and information with their environment. In detailed description, mentioned systems are organizationally close but on the other hand, are informationally open. The former is a result of a dynamical structure of the system supporting and defining the stable internal states and the latter is due to the interaction of the system with its environment. However the concept of information in the evolutionary biosystem can not be considered to be the same as that formulated by Shannon. Because the physics and thermodynamics of self-organization in biology is necessarily based on dissipative phenomena and the information flow throughout them is not a purely abstract symbol introduced by the human mind (via programmed algorithms) [5]. The syntactic Shannonian information does not involve any semantic (meaning) and pragmatic (action) physical content. Meaning and action arise from dissipative processes in which new information is generated by the living machinery in evolution, in learning (as a real self-organization process not as a result of programs previously introduced in the system) and also in action. Therefore biosystem does not copy information from the environment as a one-to-one mapping. Instead, the living system simulates its environment and builds its structure due to the coded interactions [8].

Hence it is concluded that the evolutionary behavior of biosystems and their nonlinear dynamics, as a result of informationally open far from equilibrium self-organization, lead us to adopt a nonlinear dynamics and chaos control to mimic it.

To come to the above claim, it seems that learning self-organization and evolutionary behavior of living systems and their properties in physical term is essential. Complex adaptive systems consist of many interacting and adapting components. It is known that, when a set of evolving autonomous particles or agents -such as complex molecules and cells in organisms- interact, the resulting global system display emergent collective properties, evolution and critical behavior. The particles or agents of a biological complex system are couple to each other, learn to adapt and organize, mutate and evolve, expand their diversity, react to their neighbor and to the external control, replicate and organize a hierarchy of higher order structures.

Since these behaviors organize in a hierarchical structure initiating from molecular scale, so learning how atoms or molecules self-assembled (or self-organized) to create new structures, can be a driving force in nanotechnology with the properties that go beyond the mere accumulation of their single entities. It is the

interpretation of the well known system theory principal: "the whole is more that sum of its parts".

Self-organization is spontaneous formation of organized structures, patterns or behavior from random initial conditions. While these phase transitions come from nonlinear interactions between elements, nonlinear dynamical tools are needed to explain the presence of multiple structures and also the variety of dynamics for biological self-organization. As seen in self similar structures of fractals and bifurcation in logistic map, these systems exhibit complex behavior –strange attractors- from random initial conditions. Now it is known that biological self-organization takes chaotic attractors[1] as a mechanism able to increase the variety in organizationally closed system. In this sense, the high degree of freedom and interconnectedness among particles may produce different attractors. On the other hand, external random perturbation will lead to increase internal chaotic state changemeans, means that the presence of the input (perturbation) will change the system to different attractors. The existence of various attractors as seen in living system, have the opurtunety of large initial variety in a new selection and ensure that at least some configurations will retain their stability. It is the base for learning and other surprising characteristics of an organism.

Moreover it is highly believed that living systems exist in the narrow region near the edge of chaos and it is the natural selection which achieves and sustains a stable state. As kaffman stated, when a system of simply interacting components reaches a certain level of complexity or interconnectedness, it undergoes a dramatic transition or phase changes. In other word, a system computational capability peaks in a narrow regime, between high periodic and chaotic behavior. At this critical point of a system (edge of chaos) a small change can either push the system into chaotic behavior or at the other edge, the system can achieve fixed behavior. Exactly at this point all the really interesting behaviors of a complex biological system occur. As shown in fig. 1, this is the maximum performance of the system.

Now according to the above discussion, it became definite that for mimicking living systems lying between order and chaos, and for understanding the form of organization which characterized life, computations at edge of chaos and the engineered technologies at this regime, can offer a best compromise.

[1] Attractor is a preferred position for the system, such that if the system is started from another state it will evolve until arrives at the attractor.

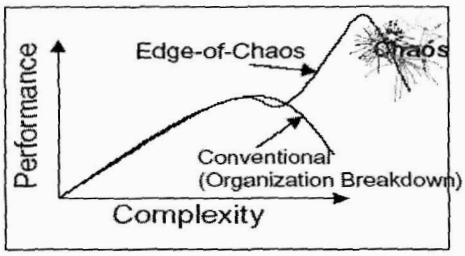

Fig.1: the performance of a complex system vrs. Its complexity

One of the approaches which can perform the computation at the edge of chaos, is recurrent neural network with a biologically adequate connectivity structure. It means that randomly connected recurrent NN in real time processing and the type of dynamics of the network can be promoting. Of course in contrast to offline computation in which, relaxation from an initial state (the input) to some terminal state (the output) is done without any external influences, Input driven recurrent NN will support a large diversity of complex real time computation and can meet our expectations.

An input driven recurrent network consists of N threshold gates with states $x_i \in \{-1,+1\}, i = 1,...,N$. Each node i receives nonzero incoming weights w_{ij} from exactly k randomly chosen units. The network is driven by an external input signal u(.) which is applied to each threshold gate.

In summary, the update of the network state $x(t) = (x_1(t)...x_N(t))$ is given by

$$x_i(t) = \Theta\left(\sum_{j=1}^{N} w_{ij} \cdot x_j(t-1) + u(t)\right) \quad (1)$$

Similar to autonomous systems, these networks can also exhibit very different types of dynamics ranging from completely ordered to chaotic depending on the connectivity structure. In fig. 2, typical examples of ordered, critical and chaotic dynamics are shown. The change of parameters –both structural and incoming related parameters- can lead to phase transition, i.e. varying such parameters may lead to qualitative changes in the behavior, for example from ordered to chaos dynamics.

We will not intend to discuss more on the computational aspects of these approaches; for more information one can see [9], but to our work it is just enough to know that changing (internal and environmental) parameters can change the dynamic.

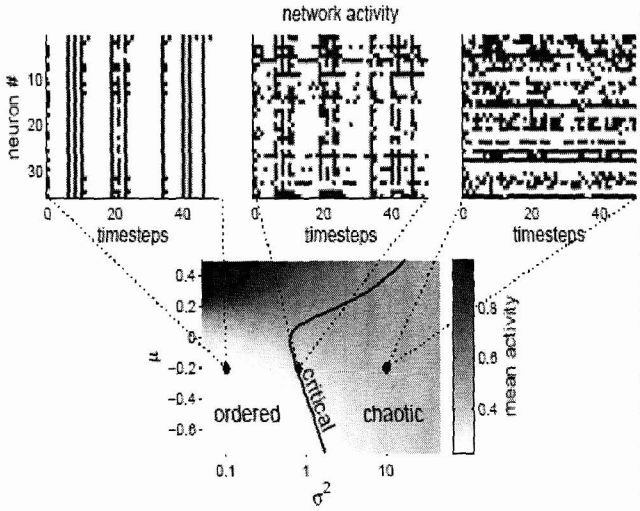

Fig. 2 : Networks of randomly connected threshold gates can exhibit ordered, critical and chaotic dynamics. The plot of the time evolution of the network state (the upper row) and the phase plot of it (the below plot) [9]

Besides the above conclusion on computational aspects of biological nonlinear dynamics, our next primary aim throughout this argument, is to introdue the necessity of control process for nonlinear atomic and molecular interactions and a possible procedure for it, to depict how the pattern formation process can be done in a proper and controlled path.

3- Control process

Since the emergent properties of an organism and generally life itself, are generated by wild interactions of nanoparticles, control over these interactions is requisite for directing and forming nanostructures in a desired way.

In natural biological systems macro molecules have an excellent control over phase stabilization, assembly and pattern formation. Also self-assembling of nanoscale building blocks in biological systems, yields a high performance, controlled size, hierarchical and compositional uniformity complex structure[2]. Moreover, selectivity and recognition at the molecular scale is a critical feature of living systems responsible for control process, i.e. the highly developed ability of biological systems to recognize designed features on the molecular scale as antibody - antigen, enzyme - substrate recognition, also the excellent selectivity of complementary biological molecules make it possible to control the formation of complex structures from nanoscales to macroscales. Note that this control process is nonlinear due to the mechanism of biological phenomena and the goals pursued. Some goals of this nonlinear control may be to cause excitation or suppression of oscillations and synchronization or transition form chaotic to periodic oscillations and vice versa.

This nonlinear control which refers to mechanisms or methods that control biological processes by exploiting the nonlinear dynamical features underlying these processes, is the base of biomimetic nonotechnology. Remember the strategies of nonotechnology as desired formation of molecular assembling. Here, the term control refers to the modification of the behavior of a nonlinear system by regulating one or more of the control parameters that govern the system's dynamics. As the dynamics or evolution of the system can be predicted by the change of its chaosity or regularity, the control of this transition is the solution for problem.

The biological control may be achieved by variations that are caused either by processes within the system or by appropriately designed external perturbation. By emulating this feature in biomimitic nanotechnology, two basic directions are introduced:

The first direction is focused on an internal perturbation, the choice of which is based on the state of the system. The perturbation changes the parameter or set of parameters of the system which results in the ordered behavior of the chaotic system. The methods focused on the choice of such parameters (perturbations) are referred to as methods with a feedback (recurrent methods).

The second direction presupposes that the choice of external perturbation does not depend on the state of studied chaotic system. The present group of methods is an alterantive to the first one and can be used in cases when internal parameters depend on the environment. Hence, it seems that by changing the dynamic of system via external or internal perturbation, the control over the structure, its formation and assembling can be achieved.

In summery, the ability to shift the dynamic of structure from an unwanted state to a desired one, will probe the phase transition, insure the correct formation of nanostructures and determine the sensitivity of dynamic to appropriate stimuli or coded interactions from environment. So, in order to have a self-organizing system or a self-assembled structure which is open -of course informationally- such a system must be able to change its structure and subsequently its attractor basins[2] due to the both environmental influence and encoded instructions within the system. In this way, the control of the system can be achieved via a choice of particular

[2] The larger area of state space that leads to an attractor is called its basin.

dynamic for a certain structure. E.g. in nanorobots this choice of dynamic is done for a certain task (performed by nanorobot) and referred to as learning. In this case, the adaptation and learning of a self-assembled structure is another challenging issue in relation to control. Again from the earlier discussion of this paper it is suggested that mimicking the functionality of biology at the edge of chaos can lead to a real adaptation and memory. In other words, the adaptation of a nanostructure -as in nano robots- must be both plastic and rigid (edge of chaos). At the start, the controller must exhibit enough intrinsic features to encompass wide range of dynamics which is a chaotic state. Adaptation will therefore be a plasticity mechanism that allows us to put constraints on good dynamics. On the other hand it must also have the power to go back into a general disorder state. Of course the path toward total adaptiveness (in the sense of adapting its own behavior and behavioral structure) rests on the principals of interaction between the nanostructure and its environment [7].

Moreover it is highlighted that the critical stage in control methodology lies in the intrinsic features of the controller, i.e. a dynamical controller for a dynamical environment. Thus for co-dependence to emerge one needs for a controller to exhibit various dynamics. Indeed, the chaotic nature of controller for any internal dynamics emerging from the collective behavior of interacting agents, is a very interesting feature. Also learning at the edge of chaos is a powerful way to assure an emerging coupling between external and internal dynamic.

4- Conclusion

In this century, the emerging of new technologies as nanobiology and molecular biomimicry, will help the dream of building evolvable self replicating machines at nanoscale, to get real. In this sense biomimicry as an interdisciplinary subject, try to extract strategies and schemes from biology and apply it to nonbiological context.

In analogy to biology, artificially self assembled structures can be controlled by imposing constraints on their interaction among themselves and with environment. In this way it is possible to determine the degree of order and symmetry of aggregates of atoms and molecules and hence the control over the structure – and thereby the properties- can be achieved by biological strategies. As argued throughout this article, the path toward best biomimicry and hence the achievements of control on pattern and structure formation in nanoscale, rest on computations at the edge of chaos. this is the point at which the nanoengineered objects, devices and architectures will best correspond to biological self assembled and self organized structures.

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