DESIGN CREATIVITY AND SYSTEM ADAPTABILITY: A DNA BASED AND SELF-ORGANIZING APPROACH

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Introduction

Research on design creativity has mostly been concerned with understanding how human designers create their design ideas and with developing better ways to help designers be more creative. Another drastically different way to pursue the same research is to investigate how Mother Nature created and keeps creating new creatures and novel phenomena. Bio-mimetic design is an evolving area where researchers attempt to find ways to take advantage of the "design ideas" that the nature has already created (Sarikaya 1994, Vincent and Mann 2002, Chu and Shu 2004). Furthermore, using genetic algorithms and genetic programming techniques, which somehow mimic the "idea generation" process of the nature; researchers were able to use computers to help generate novel solutions to some engineering problems.

Putting aside the philosophical discussion, we may observe that human design and natural design are very much distinct from each other: human design is more purpose or function driven and takes a top-down approach, while natural design is arguably much less purposeful and follows a bottom-up approach. These two forms of design are dictated by the difference in the ways the designs are realized. Humans can make things the way they want so that the realization can be actively pursued. The nature, however, does not "make" things happen. It "lets" things happen: the things "self-organize" themselves under given situations by following natural laws. It can be argued that the creativity in the nature exists among the "self-organizing" based option generation and "survival driven" choice making.

Our research on self-organizing based design creativity is motivated by an investigation of developing complex adaptive systems such as environment-adaptable robots. We are interested in combining the advantages of human and natural design methods and design systems that can design and build themselves by following a self-organizing strategy that on the one hand recognize the functional needs and on the other hand explore creative opportunities through self-organizing.

A DNA Based and Self-Organizing Approach

For a system to adapt to endogenous changes caused by the system itself (e.g., due to malfunction or system damage) and exogenous ones from the environment (e.g., unpredicted obstacles or change in temperature), it must be able to recognize emerging functional needs, create and implement solutions to deal with the changes. We take a DNA based and self-organizing approach to developing such adaptive systems. The basic idea is two-fold. First, to allow a system to exhibit adaptability the system must be able to self-organize itself in case of situational changes, endogenous or exogenous. Second, for an adaptive system to maintain its designated functionality, it must possess mechanisms that allow the system to keep its functional information and regulate its self-organizing processes for achieving the functions. The key challenge we face in this approach is how to identify and maintain the appropriate balance between pure self-organizing which is an almost purposeless process and "human-based" design which is purposeful and almost entirely function-driven.

We look into biological systems (Audesirk et al 2001) for insights and attempt to explore a *biological synthesis* method for complex adaptive system design. Natural systems including animals and plants are highly adaptive to their changing environments and can be viewed as *ultimate* adaptive systems. The *principles and mechanisms* employed by them provide us with both inspiration and specifics. Common to all biological systems, *cellular structure* is indispensable for these systems to grow, reproduce, and adapt. To design and create highly adaptive engineered systems, we need a *cellular* or *cell-based* product definition framework that treats a product as a composition of cells or cellular components as opposed to the components in the traditional sense. Furthermore, achieving high adaptability requires *dynamically* create, capture and apply *design information* pertaining to the designed functions and changing environmental and operational situations. Biological DNA in nature plays the essential role in keeping, maintaining and transferring such "design information", i.e., genome, within and between individuals. Resembling biological DNA, we need to develop a rich synthetic *design DNA*, or *dDNA* for short, scheme that can be used to create, capture and maintain design information throughout the product lifecycle. With the *cellular structure* capable of self-organizing and *dDNA* capable of generating, maintaining and modifying design information, it may become possible for us to develop a new kind of *mechanical lifelike adaptive systems* that can adapt to the changes of the system itself and those of the environment by following mechanisms that are similar to those found in biological systems. The research questions are: *What is design DNA? What is mechanical cell? How can design creativity be modeled or embedded in design DNA operations? How does cell self-organizing can lead to rich phenotypes and hence richer phase space of the system?*

Cellular System Formation and Representation

To answer the first two questions, we need a comprehensive representation framework that maps biological system concepts into mechanical systems. Figure 1 illustrates our *cellular system formation & representation (cFORE)* scheme that is being developed to facilitate DNA-based and self-organizing adaptive system design.

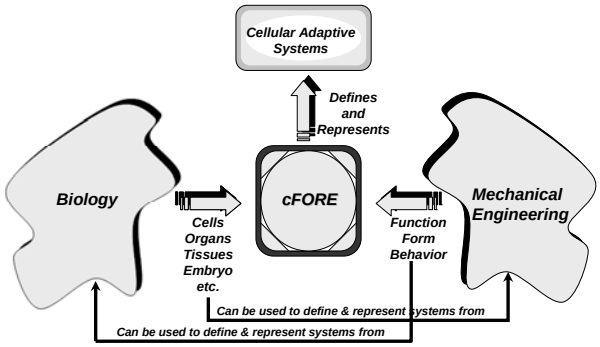

Figure 1 cFORE Representation Model Schematic

The research questions for cFORE are as follows: *(1) To what extent can we apply the concepts and processes of biological systems to the development of mechanical systems? (2) Can the notions of function, form, and behavior be defined in terms of biological concepts? (3) Can concepts unique to biology such as cells, organs, tissues etc. be used towards the definition and representation of mechanical systems? (4) Can a system design representation model be created based on concepts exclusive to biology while still harnessing critical elements such as function, form, behavior from mechanical design?* Following are some key concepts introduced in cFORE.

Definition 1 - Mechanical Cell: A mechanical cell, *mCell*, is defined as:
mCell = {Cu, $(f),(\phi)$, dDNA, Es, Ec, Mc}, where, Cu: control unit (nucleus), dDNA: design information (DNA), (ϕ): centroidal location, (f): 6 sides, Es & Ec: energy storage & converter (mitochondria), Mc: material converter (lysosomes), as shown in Figure 2.

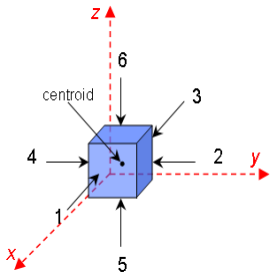

Fig 2: Mechanical Cell

Definition 2 – dDNA (sGenome): *dDNA*, seen in Figure 3, is a matrix representation containing the system's genome, sGenome.

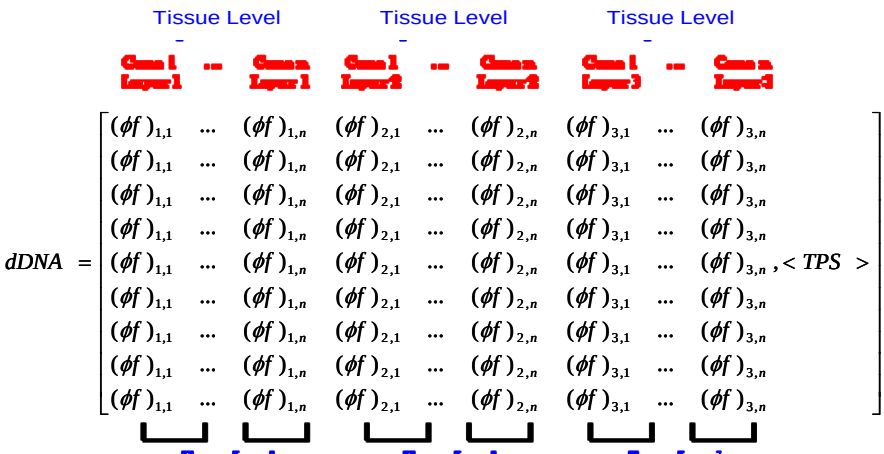

Figure 3: Multilayered *dDNA* Structure

The sGenome contains information regarding cellular function layers (germ layers), leaf functions (organs), solutions (tissues), design genes (genes), cellular locations (ϕ), cellular functions (f), and self-growth instructions (transcribed protein sets or *TPS*). In the figure one can note that cellular functions (f) and locations (ϕ) are organized into *gene sets*, gene sets are sorted into *tissues*, tissues are grouped into organs, and organs are arranged into germ layers, in a similar way as seen in biological systems.

Drawing inspiration from the concepts of germ layer formation (Wilt and Hake 2004), we introduce the concept of Cellular Function Layers. We define three layers: *Energy-Material Layer* (inner germ layer), *Structural Layer* (middle layer), and *Interface Layer* (outer layer). The Energy-Material Layer involves those components / subsystems which will be responsible for the conversion of energy and materials.

Definition 3 - Cellular Functional Layers (germ layers): Given a finite collection of organs *O*, a germ layer *GL* may be defined as,

$$GL_k \supset \{(O)_{k,1},(O)_{k,2},\ldots(O)_{k,n}\} \quad where \quad k=1\ldots3.$$

The steps for the development of the embryo from 3 function layers into a fully functioning system will be as in biology.

Definition 4: Leaf Functions (Organs): Given a finite collection of tissues *T*, an instance of *O* organs may be defined as,

$$O_{k,L} \supset \{(T)_{k,1},(T)_{k,2},\ldots(T)_{k,n}\} \quad where \quad k=1\ldots3 \quad and \quad L=1...n.$$

Tissues are used to group genes into behavioral sets. The number and types of tissues are a result of the design and are obtained through the use of morphology tables.

Definition 5 - Solutions (Tissues): Given a finite collection of genes G, an instance of *T* tissues may be defined as,

$T_{k,L} \supset \{(G)_{k,1},(G)_{k,2},\ldots(G)_{k,n}\}$ *where* $k=1\ldots3$ *and* $L=1...n$.

Genes are used to group cells into collective sets. In biology genes are used to store the characteristics of a particular system. Namely if a bio-system has black hair or brown eyes etc., that information is stored in the system's DNA through genes. Similarly we define genes as a grouping of cells into desired geometric shapes dictated by the system's design. The amount of genes found in each of the three germ layers is also dependant upon the particular design of the system.

Definition 6: Design Genes (Genes): Given a finite collection of cells C, an instance of G genes is defined as,

$G_{k,L} \supset \{(\phi f)_{k,1},(\phi f)_{k,2},\ldots(\phi f)_{k,n}\}^T$ *where* $k=1\ldots3$ *and* $L=1...n$.

Definition 7-Cellular Layer: Cellular functions (f), Cellular locations (ϕ)

$(\phi f)_{m,n} = (x,y,z,(f_1\ldots f_n)_1,(f_1\ldots f_n)_2,(f_1\ldots f_n)_3,(f_1\ldots f_n)_4,(f_1\ldots f_n)_5,(f_1\ldots f_n)_6)_{m,n}$

whereby x, y, z are the coordinates of the cell's centroid defined with respect to a relative coordinate system and $(f_1\ldots f_n)_1\ldots(f_1\ldots f_n)_6$ are the set of functions each of the 6 cellular faces are able to perform. The index *m*, *n* is used to represent the germ layer number and gene number, respectively.

Definition 8 - Transcribed Protein Set TPS (self-growth instructions): *TPS* is defined as a collection of three types of proteins,

<transcribedProteinSet> : : = <enzymes><structuralProteins><transductionProteins>
<enzymes> : : = <cellularFunctionExpressionProteins><formationProteins>
<cellularFunctionExpressionProteins> : : = <eAminoAcids><gAminoAcids>
<formationProteins> : : = <fAminoAcids><gAminoAcids>
<structuralProteins> : : = <sAminoAcids><gAminoAcids>

In biology, amino acids are the basic structural building units of proteins. There are roughly 20 amino acids which when grouped in certain orders and sequences can generate a very large number of unique proteins. Similarly we define a group of amino acids and group them into 4 sets seen below.

<gAminoAcids> : : = <(x,y,z), F1, F2, F3, F4, F5, F6, &>: General amino acid that stores centroid location (x, y, z), mechanical cell face information F1 through F6 and the "&" character.

<eAminoAcids> : : = <f1 f2 ... fn>: Expression amino acid that stores cellular functional expression instructions.

<fAminoAcids> : : = <u d l r f b A D #> formation amino acid that stores the formation instructions. u, d, l, r, f, b, A, D, # stand for up, down, left, right, forward, backward, attach, detach and an integer value respectively.

<sAminoAcids> : : = <c>: Structural amino acid that stores construction instruction, c.

An example of a protein composition of amino acids is: <fProtein1> = (2,1,6)DF3d1AF3(1,1,5)AF1, which states that the cell at centroid location (2,1,6) should detach face 3, move down 1 and attach at its face 3 the cell at centroid location (1,1,5) at its face 1.

Concluding Remarks

We have just initiated a research aiming at developing systems that can reinvent themselves to deal with various unpredictable changes in their operation environments. One key issue in this research is how we can make systems *self-create* new designs and *self-grow* new capabilities based on the newly created designs. From a design creativity's perspective, what is needed is to embed "creativity" in systems and make them self-creative. We look into biological systems for inspiration and insights and are developing an approach that combines human design and natural design to attain both functionality and adaptability. As a first step of this research we developed a conceptual mapping of design and production between natural and man-made systems. The cFORE framework is being developed to capture both design information and production process. Our ongoing research explores mechanisms to apply *dDNA* to generating new designs and reinventing systems.

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