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A NOVEL EVOLUTIONARY METHOD FOR SYNTHESIS OF 3D CONTINUOUS STRUCTURES

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ABSTRACT

The design of complex structures which benefit the usage of inhomogeneous properties is a very difficult task. In this paper we present a novel approach in which we synthesize the design of structures by mimicking two fundamental processes from biology - Evolution and Development. We will show that by using these two processes in a computational model, we are able to evolve high performance structures. These structures contain a high degree of complexity from a topological aspect and from a materials distribution aspect. This degree of complexity is difficult or even impossible to achieve by ordinary design methods.

1   INTRODUCTION

The development of design synthesis methods has recently become an active area of research. The idea is to generate novel sets of design configurations that exhibit high performance properties. These designs may not be able to be created by an engineer using standard design techniques. An early contribution in this area [1] begins with engineering requirements and subdivides a given spatial domain into a fixed number of finite elements with well-defined boundary conditions. The optimization procedure finds the optimum structure by removing the lightly loaded elements leaving only those which form the optimum structure. A different approach [2] demonstrates a way to synthesize a compliant two-dimensional MEMS device by eliminating cells from a fixed mesh according to the evaluation of three

parameters. From a mathematical point of view both these methods find the optimum configuration from a finite set of configurations (large but still finite) determined by the initial mesh. This restriction dramatically limits the ability of each method to find a global optimum. Since, for a given design problem, the total number of possible configurations is generally infinite. Another disadvantage of using a fixed mesh is the inability to generate arcs and curved objects without using large number of elements. The method presented here addresses these issues using a different approach such that the space of possible configurations is infinite and the elements are not restricted to a single shape but are allowed to be deformed and differentiated. In this way smooth, curved, inhomogeneous structures can be synthesized.

Inhomogeneous structures can be useful in many areas including optics, mechanics, thermal management, etc. In optics, for instance, several layers of thin films create an optical filter. Each layer has different properties which make the design of such filters highly complex. Different methods have been developed for the synthesis of such filters. J. Skaar [3] has shown a way to synthesize optical thin-film filters with inhomogeneous properties such that each layer in the film has a different number of reflectors. Yang and Kao [4] introduced a way to evolve the structure of a thin film with inhomogeneous optical coatings such that the evolved structure has the functionality of a beam splitter and a narrow-band reflector.

In addition to the large variety of applications, new techniques have been introduced such that the ability to fabricate

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highly inhomogeneous structures is possible. These methods include molding and micromolding techniques [5] which enable inhomogeneity to be produced at the scale of a single micro-drop.

This paper introduces an approach that is inspired by biological growth and development processes. Biological structures are frequently inhomogeneous, and one of the main engineering functions of these structures is to maintain low mechanical stress when subjected to external loads [6]. An example of such structures are bones which are characterized by an ability to carry high dynamical loads but are still relatively light. The material structure of bones is highly complex which makes them difficult to be replicated with contemporary engineering techniques. The growth process of bones has been studied by several researchers who looked for the factors that stimulate growth. It was shown by Vander Sloten and Van Cleynenbreugel [7] that mechanical stress has a crucial effect on the behavior of bone cells during growth. They observed that under the influence of mechanical stress, bone cells tend to divide more rapidly than when unstressed.

The shape of biological structures has been an inspiration for an enormous number of designs [6]. The obvious example are aircraft that have a topological similarity to birds. The precise process by which nature has been able to produce such high performance structures both in shape and in complexity is not yet fully known. However, it is well known that the building blocks of each biological structure are cells. During the growth and development process cells execute a set of steps encoded in an organism's DNA. These steps are controlled by genes, where each gene has different functionality. Once the individual has reach maturity the rate of the growth process is attenuated, and is ultimately stabilized in its final configuration.

Inspired by all of these ideas, a model has been implemented here which mimics some of the fundamental issues of biological growth and evolutionary processes. We have created a three dimensional evolutionary and development model for structures [8]. The structures (phenotypes) were evolved to hold an external load in the form of wind. The wind has been exerted randomly on the phenotypes during their growth process. Phenotypes which developed high stresses or phenotypes which were too heavy or both, received low fitness evaluations.

Our model contains artificial cells which are the building block of every phenotype. Cells in this model are an extended three dimensional finite element. In addition, every cell has an artificial genome that contains genes. Genes in our model can be interpreted as a *rule* set which is composed of two parts *if* condition - *then* action. The condition part usually relates to the "environment effects" which are sensed by the cells through chemical diffusion. The action part represents an operation , such as cell division, cell differentiation, cell adhesion, etc. Sections 1 through 3 of the paper start with a description of the model and will focus on the developmental process within the model. A description of the basic elements in the model will be given.

These elements includes; genes, morphogens, signalling mechanisms, and the genome. We we will also briefly described two additional important mechanisms; diseases and metabolism. We will explain their necessity to the success of the model. Section 4 shows the phenotypes that were evolved in our model. We have simulated evolution and development of phenotypes that need to sustain loads generated by wind. We will show that the evolved phenotypes contain a high degree of modularity both in topology and in their internal structure. This problem has common roots both in the engineering and the biological world. In section 5 we will provide our conclusion and understanding based on the results.

2 Artificial Model

In the work reported here, an artificial model of structural growth has been created which is an extension of previous work done by the authors [8]. The two critical fundamental elements of this work are the selection of the artificial cell (the basic structural element) comprising each individual, and the artificial genes (the rules) which are evolved into the genetic information of each individual. The genetic information of an individual is shared by all of its cells. Each individual cell executes its rules until a mature structure is formed. Once maturity is reached, an evaluation scheme determines the fitness (performance) of the structure. Evolutionary operations (selection, crossover, and mutation) alter and refine genetic information in a population of individuals over multiple generations. The results are structures that meet the desired performance goals.

Mimicking nature, the basic structure of a gene is an *if*-conditional *then*-action rule. During the natural embryogeny of organisms like plants, every 3-D region can deform according to nine different geometric operations: one for isotropic growth, two for anisotropic growth (B), three for shear (S) and three for rotation [9], illustrated in Figure 1. In the artificial embryogeny presented here, the geometric operations (excluding the three for rotation) are defined as actions, and as with natural embryogeny, every geometric operation is assigned a unique alphabetic letter as shown in Table 4).

In addition to the geometric operation actions, cell-type actions are defined, as shown in Table 3. These actions are the three basic operations that occur in the developmental process of every biological structure, including; cell division, cell death, and cell differentiation. Cell division splits the cell into two equally sized cells, such that the total volume of the divided cells remains the same as that of the initial single cell. Cell death causes a cell to be removed from the model. Cell differentiation alters the material properties of a cell.
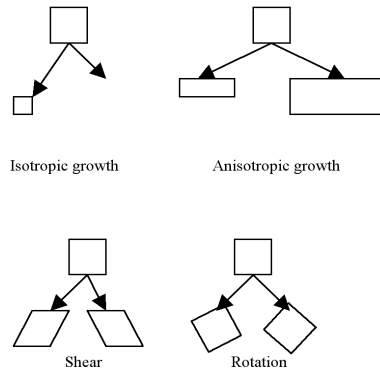
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Figure 1. The four basic geometric operations observed in sub-regions of plants.

2.1 Environment

The environment in which the individuals are grown contains factors which every cell can sense and which may affect the way genes are expressed. The relationship between the information that cells receive from the environment and the development of the phenotype is not predetermined. Rather, conditionals are available to the evolutionary process that sense the concentration or gradient of each morphogen. In this way, the evolutionary process establishes the relationship between information, growth and development.

In the artificial embryogeny presented here, two kinds of morphogens are present. The first represents a source that drives the growth of the phenotypes toward it. This morphogen is produced continuously at a predefined location and diffuses through space, impinging on the walls of each cell. The second morphogen represents the surface of the ground to which cells adhere when they intersect the surface.

As the phenotype is being grown, it is evaluated by means of a finite element analysis to determine the pattern of mechanical stresses and deformations in the phenotype [10]. Every cell is an extended 3-D non-orthogonal finite brick element. Therefore, the structure and the mesh are identical, and are evolved simultaneously during growth and development. Cells also maintain information relating to their size, age, and distance from neighboring cells. Each type of information available to each cell is identified by a lower case alphabetic character, shown in Table 1.

2.2 Genome Structure

The genome contains words which contain genes with their corresponding letters (Tables 2 through 4). Every word starts with the letter "R" which indicates the number of times the particular word will be executed. The letter "Z" indicates the beginning of the word. The genes contain operations, parameters (*e.g., morphogen concentration or gradient*) and coefficients. Similar to transcription factors in nature, coefficients are numbers between zero and one, that scale an effect in proportion to the chemical to which they refer.

3 Control mechanisms
3.1 Conditionals

The conditional artificial genes are "veto" or "suppression" genes. These genes affect other genes only at the genome level, by turning actions off or on according to whether the conditional test is satisfied or not. This is shown in Table 2.

3.2 Metabolism and Thermodynamics

A thermodynamic energy consideration is present in the model which balances the maintenance of the organism mass with the creation of new mass [11]. The amount of energy E_c that each cell may consume, in a given time step, Δt, is proportional to its metabolic rate, B_c. Part of this energy is used for maintaining the existing phenotype while the remaining energy may be used for creation of new mass, as shown in Equation 1,

$$E_c = E_0 B_c \Delta t. \tag{1}$$

The cell's metabolic rate is proportional to the size of the phenotype S and can be determined using Kleinberg's law, given in Equation 2,

$$B_c \propto \frac{S^{3/4}}{N_c}. \tag{2}$$

Every gene's execution consumes energy. By specifying the amount of energy for every gene and by establishing E_0, a thermodynamic size limit can be specified for the phenotypes, as shown in Equation 3.

$$E_c = E_0 \frac{S^{3/4}}{N_c}. \tag{3}$$

The specification of energy needs to be determined by the user based on his experience with the model. Even when the phenotype reaches the thermodynamic limit, this approach will permit new mass to be created at the expense of removing existing mass, potentially changing the topology of the phenotype.

3.3 Diseases

A disease can only occur as a consequence of a defective genome. Examples of diseases in phenotypes include unlimited

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production of cells or production of cells that are significantly distorted. Once a disease has been detected, an artificial immune system attempts to eliminate it using several methods (*e.g.*, refining the mesh). If none of these methods work, the phenotype itself is eliminated, but not before it is evaluated and penalized for being incapable of reaching maturity.

3.4 Evolutionary Scheme

The evolutionary scheme is derived from a genetic algorithm with three steps: selection, crossover and mutation, and each repetition is defined as one generation. The algorithm is initialized with a set of randomly generated genomes. Starting from a single artificial cell, one individual is grown from each genome by executing the rules it contains. Once each individual reaches maturity, its fitness is evaluated by means of the finite element analysis and the aggregation of additional properties.

4 Results
4.1 Configuration and synthesis of structures

The approach outlined above has been applied as an experiment representative of an important problem in engineering and nature. The problem was to synthesize the configuration of a structure to support a highly varied load generated by a wind. In addition, the structure needs to reach a certain height which increases simultaneously with the evolutionary process. For this problem, two morphogens are present in the environment. One morphogen represents a source that provides incentive for phenotypes to grow toward it. This source sets desired height of the structure. The other morphogen represents the ground. In addition to the two morphogens, the phenotypes are exposed to external forces. The first one is gravity, which is generated equally on the cells. The second force is similar to a force generated by wind, which is proportional to the projected area of the phenotypes. In our model, the wind is not constant but rather changes randomly during the growth process. Two kinds of materials may be utilized by the algorithms, steel and aluminum. The goal was to evolve phenotypes(structures) which utilized both material within a uniquely evolved topology. The fitness evaluation function was composed of six parameters: distance of the phenotype from the light source, age of the phenotype, weight, cell morphology, cell volume and the maximum mechanical stress on the cells. All of these parameters were aggregated to a single scalar through a unique aggregation function.

Figure 2 and Figure 3 show four different view of two phenotypes that have been evolved for several hundreds of generations. The colors of the cells in Figure 2a and 3a represent the distribution of mechanical stresses inside the cells. Green represents low stress and it graduates to red which represents high stresses. We can see that none of the phenotypes are over stressed. Figures 2b and 3b show the cell's materials distribution

in the phenotypes. We can see that both phenotypes are inhomogeneous such that there exists regions of adjacent aluminum cells and regions of adjacent steel cells. A distinction between these regions are presents in Figures 2c,and d , and Figures 3c, and d.

The growth and development process which creates a phenotype from a single cell is illustrated in Figure 4.

The difference between both phenotypes in terms of performances is small. Both phenotypes have lower stresses and are relatively light. They also grew to the desire height. From a topological view, both phenotypes are completely different. The phenotype in Figure 2 looks similar to a bar. The bar contain cross-sections with areas that ranged from high to low, from bottom to the top, respectively. We can also see that the inner part of the bar is made from aluminum Figure 2c, while the outer part made from steel Figure 2c. The second phenotype in Figure 3 has a topology which is similar to a two piece arc. The arc has two regions - upper and lower. The upper region is made from aluminum Figure 3c and the lower region is made from steel Figure 3d.

The fact that both phenotypes contain regions of different materials instead of a random distribution is very encouraging. Phenotypes in nature share this type of property. Bone for instance has regions of materials with different mechanical properties - trabeculae in the center part and osteon in the outer part of the bone. A similar structure has also been seen in the phenotype in Figure 2.

5 Conclusion

A new method has been presented, using a biological approach to growth and development of configurations of inhomogeneous structures. The challenges of creating designs that can take advantage of these advanced materials require formal structured design synthesis techniques, such as the one presented here. The model has been tested against a fundamental engineering problem that is observed in nature as well. The utilization of two different materials, aluminum and steel, and the configuration (topology) of the structures, was optimized by the evolutionary algorithm. The evolved phenotypes have different topology but similar materials distribution. Instead of a random distribution, regions of materials were seen in the phenotypes. This use of materials made the phenotypes light and yet able to support the external load. Similar characteristics are seen in biological structures such as bones, trees etc.
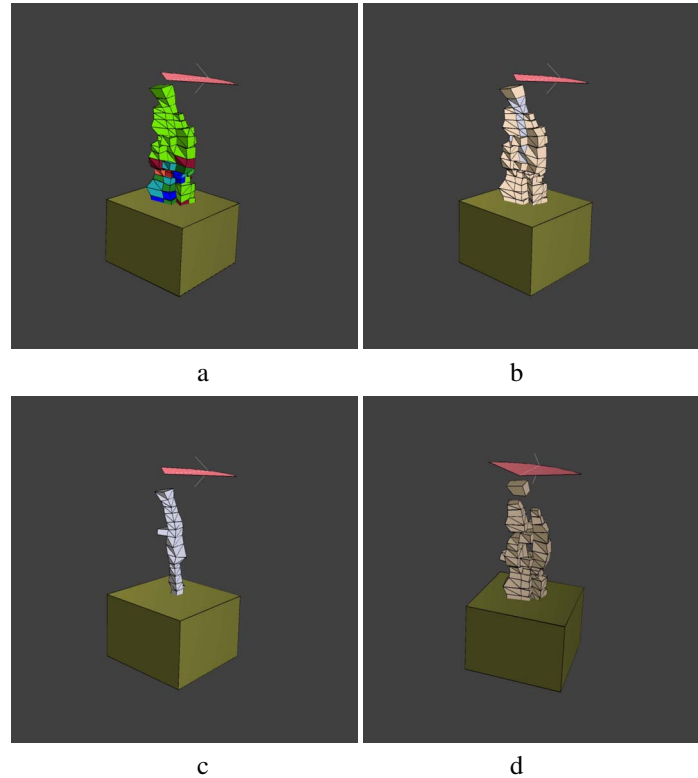
6 Acknowledgments

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Figure 2. Inhomogeneous Structure - four different view of the phenotype. a) colors represent mechanical stresses. b) colors represents material, brown for steel , gray for aluminum. c,d) The portion of cells that made from aluminum and steel respectively.

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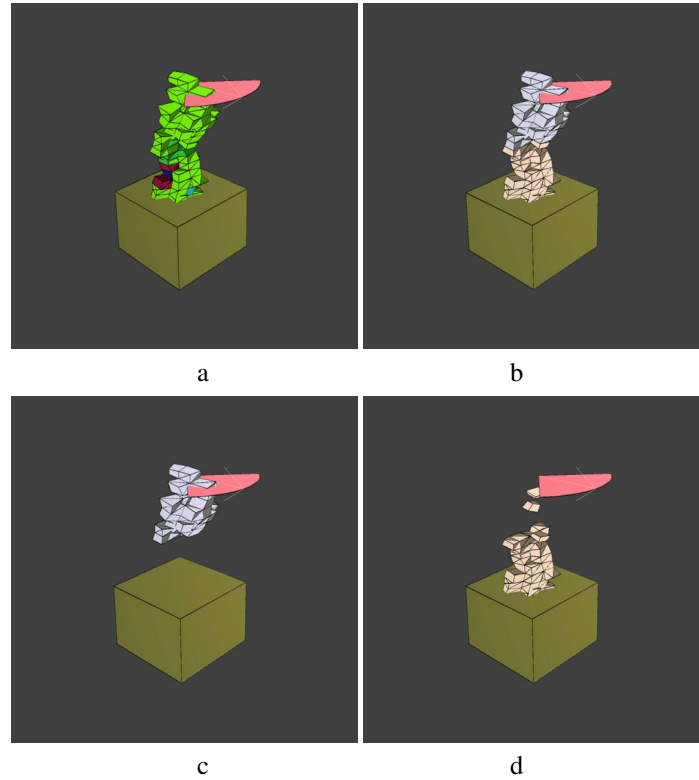
Figure 3. An inhomogeneous Structure - four different view of the phenotype: a) colors represent mechanical stresses; b) colors represent material, brown for steel , gray for aluminum; c and d) the portion of cells made from aluminum and steel respectivley.

Table 1. Cells Chemicals

ID	Description
a	Maximum principal stress normalized with the yield stress
b	Middle principal stress normalized with the yield stress
c	Minimum principal stress normalized with the yield stress
d	Principal vector correspond to the maximum principal stress
e	Principal vector correspond to the middle principal stress
f	Principal vector correspond to the minimum principal stress
g	Cell volume
h	Morphogen direction
i	Morphogen diffusion intensity

Table 2. Veto (conditional) genes

ID	Name	N^1	Possible Parameters
V	Suppress if below	1	$(a,b,c,g,i)\times$ fractional coefficient
W	Suppress if above	1	$(a,b,c,g,i)\times$ fractional coefficient

$^1N =$Number of Parameters

Table 3. Cell-type operation genes

ID	Name	N^1	Possible Parameters
D	Cell division	1	(d,e,f,h)
K	Cell death	0	
F	Cell differentiate	1	$(1,2,...^1n)$

$^1N =$Number of Parameters
$^1n =$Number of different cells

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t=0   t=15   t=30   t=40   t=50   t=62
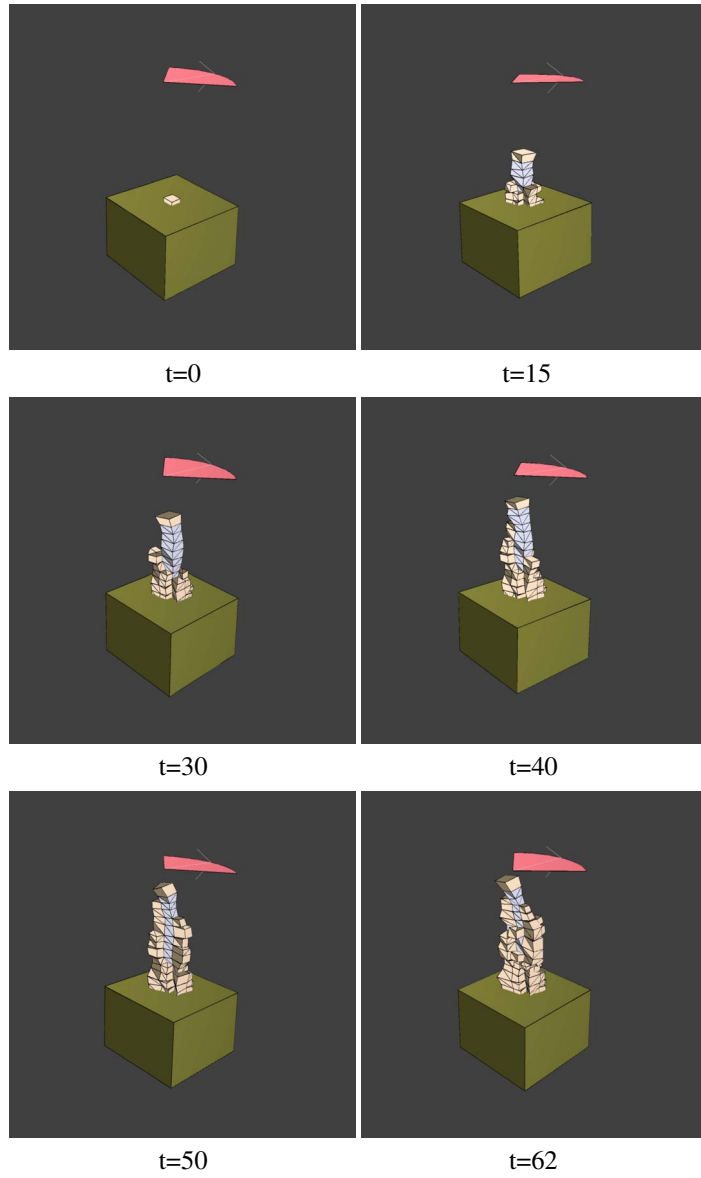
Figure 4.   Growth process of the phenotype in Figure 2.

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Table 4. Geometrical operation genes

ID	Name	N^1	Possible Parameters
A	Shear	1	$(d,e,f,h)\times$ fractional coefficient
B	Anisotropic growth	3	$(a,b,c,g,i)\times$ fractional coefficient
C	Isotropic growth	1	$(a,b,c,g,i)\times$ fractional coefficient

[1]$N =$Number of Parameters

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