Design Gene Representations for Emergent Innovative Design

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Abstract. Looking to nature for inspiration, this work presents an alternative bottom-up engineering design system, which allows unpredicted-but-valuable designs to emerge with few constraints. A set of "design genes" have been developed which trigger and control the growth of a design within a CAD system through mechanisms such as copying and stretching. The single gene is structured as a one-dimensional array representation, which includes 6 elements: the attribute, the attribute's value or type, its active status, start and stop conditions, and dominance. A set of genes grouped together forms a "design seed" which contains all the necessary information to create the design. The design then emerges from the actions of the genes, which do not know anything about the final shape or form of the design. The growth is managed within a design environment which provides the external triggers and conditions needed to activate the genes. Different designs can emerge from the same seed in response to different environmental conditions based on their influence on the elements in the genes. This paper will outline the design gene representations and a simple-but-powerful growth strategy for the emergence of innovative designs in engineering. Numerical examples are tested to demonstrate the effectiveness of the system.

Keywords. Bio-inspired design method, Design gene, Innovative design, Tree growth, Additive Manufacture, Engineering Design.

1. Introduction

Continuing innovation is essential to bringing ever better products to market. The diversity of products has resulted in a range of frameworks which take different approaches to design, such as set based design [1] and TRIZ [2]. These systems and processes allow control, predictability and traceability of decisions to help the engineering enterprise succeed in what can often appear to be an impossible scenario due to the complexity and number of decisions to be made. Once a concept is agreed it is developed from top to bottom. A key drawback of these systems is that innovation is stifled, because designers are heavily influenced by those they already know, and new designs are often mere perturbations of existing designs. To avoid predicted solutions, a new design system and philosophy is required.

Nature is the ultimate source of inspiration for innovative designs in engineering [3-7]. For example, tree growth [8-9] in nature exhibits superior characteristics such as

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bottom up, unconstrained and unpredictable growth, as well as adaptability, and self-reconstruction which are highly desirable in engineering. There are a myriad of variations, yet a tree is always recognisable as a tree with key common characteristics across all types (e.g. trunk, branch, and leaf). Inspired by this, this work aims to design products by allowing the design to emerge from a design seed and grow to meet requirements, within a given environment. To meet this aim, the key questions are: can design be defined at a more elemental level and allow variation to emerge due to environment? What triggers the decision on how to grow or to modify a design feature? Conceptually, are there design genes that could drive the product form and function?

Our ambition is to develop a new bottom-up design system that caters for multi-disciplinary problems. Here, the first steps are taken to examine this concept and investigate the plausibility of defining design genes for simple structures, to establish if they can grow more complex functional shapes. More test cases for this concept and innovative designs for additive manufacture are discussed in companion papers [10, 11].

2. Design genes

In the proposed design system, the design emerges from a seed following a growth strategy influenced by an environment. As far as possible, the design must emerge rather than being tightly controlled with predictable solutions. To achieve this, basic principles, definitions of genes and seeds, and algorithms for growth, are needed.

2.1. Principles

Tree growth is incredibly complex and far from being fully understood. However, several useful principles have been identified, and captured to help guide development of practical algorithms of design growth in the field of engineering design. The principles are listed as follows:

1. A design gene does not know the consequences of the decisions it makes.
2. A single design gene can describe only a single attribute.
3. A single design gene comprises 6 elements: attribute, attribute's type or value, active status, start and stop conditions, and dominance.
4. No genes with the same attribute can have the same dominance.
5. A set of design genes is contained in a design seed.
6. One design seed can grow only one structure.

2.2. Design genes and seed

Considering the development of a tree, the action of its genes determines the final form. The same set of genes (or genome) creates leaves, branches, and roots and so on. The leaf doesn't plan to become a leaf, it just happens as the tress develops. Thinking of the genes as switches helps in understanding what is happening. For example, if the gene for 'branch' is active, then the branch will occur, otherwise it lies dormant and inactive in each growth step during development. Design genes act as instructions to allow structures to emerge during the process of design growth within a given engineering environment. They are used to trigger and control the growth behaviour.

Design gene: this is the basic geometric and functional unit of heredity. Based on the principles 1, 2 and 3 stated in Section 2.1, a design gene can be structured as a $(\mathbf{1} \times \mathbf{6})$

array representation, string or sequence, of real values which represents the heredity of a design, i.e.: **gene = [attribute, value or type, active status, start condition, stop condition, dominance]**

- Attribute – that describes properties of the seed, for example:
  Direction: to determine where the seed can grow in each growth step;
  Cross section shape: to determine in what kind of shape type the seed can grow.
- Value/type – expression of the attribute.
- Active status – either 0 or 1 that represents working status of the gene: "0" means the gene is not working; while "1" means it is working.
- Starting and stopping conditions – within which the gene remains working once its active status is set to 1. The condition can be given as a threshold value of variable(s) of interest.
- Dominance – a real number between 0 or 1 that describes priority of the gene, with 1 indicating a dominant attribute which overrides an attribute with 0.

For example, a typical design gene could look like: **gene = [Cross section, Circle, 1, 0.0, 1.5, 1]**

This single gene can be explained as: the cross-section type (see column 1) of a geometry is circle (see column 2); the gene is active (see column 3: active status = 1) and its working conditions are Height $\geq$ 0.0 (see column 4) and Height $\leq$ 1.5 (see column 5), and it has priority (see last column: dominance = 1).

Design seed: this is a collection of design genes which characterize a complete design. A typical design seed can be structured as a $(\boldsymbol{n} \times \mathbf{6})$ multidimensional array. A seed including 6 design genes is shown as bellow:

gene1 = [DirectionX, 0, 1, 0.0, 1.5, 1]
gene2 = [DirectionY, 0, 1, 0.0, 1.5, 1]
gene3 = [DirectionZ, 1, 1, 0.0, 1.5, 1]
gene4 = [Cross section, Circle, 1, 0.0, 1.5, 1]
gene5 = [Length, 0.5, 1, 0.0, 1.5, 1]
gene6 = [Radius, 0.2, 1, 0.0, 1.5, 1]

In order to successfully grow a design, the genes that represent respective growth direction, cross-section shape and magnitude are mandatory in a design seed.

Algorithm: a nested loop for scanning and checking of each element in each gene in each growth step

Input: A seed with genes and its position
Output: An unpredicted-but-valuable structure

```
1:  For each gene
2:    For each element of the gene
3:      If active == 1, then
4:        If start and stop conditions == true, then
5:          Check the dominance
6:          Grow a CAD model in CADfix with API
7:        End If 4
8:      End If 3
9:    End For 2
10: End For 1
```

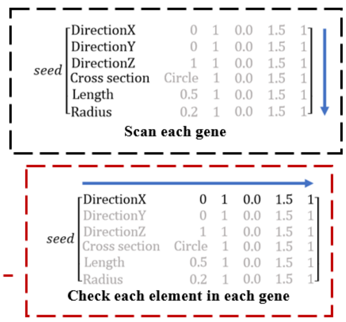


Figure 1 Illustration of main algorithm driving the growth

2.3. Algorithm for growth

The growth process of a design is assumed as an iterative loop incremented at each growth step. During the growth process, a strategy of **scanning and checking for each element in each gene** in each iterative step is adopted to guarantee the growth occurring. An emergent CAD model will be updated in each growth step based on the genes and the growth algorithm using CADfix software with API. This simple rule allows for preliminary investigations of the concept. The core algorithm to highlight how the genes are used in creating a CAD model is illustrated in Figure 1.

2.4. Concept Illustration

Case 1: A design grows from a seed located at (0, 0, 0) comprising 6 design genes, as defined in section 2.2. With reference to the gene sequence shown in the dashed box in the algorithm for growth in section 2.3, gene 1 to 3 specify that growth direction of the seed is the vector [0, 0, 1]. i.e.: Z axis; the cross-section shape of the geometry is specified to be a circle in gene 4; gene 5 and 6 determine length and radius of this cylinder entity are 0.5m and 0.2m, respectively; The active status and dominance for each gene are all set to 1. The start and stop conditions for each active gene are given as Height $\geq$ 0.0m and Height $\leq$ 1.5m, respectively. Due to the working conditions and principle 5 and 6, this seed can grow until step 4. Finally, a 2.0m high cylinder CAD model emerges. Details of each growth step are shown in Figure 2. It can be seen from this case that the high fidelity of gene copy from current step to next step is essential to a design growth.

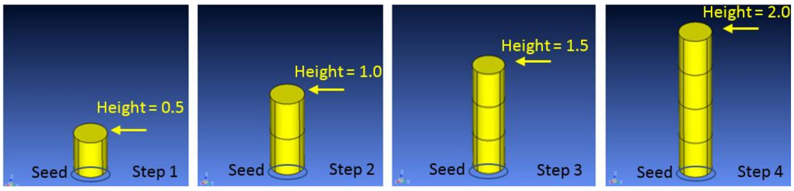


Figure 2. A design growth from a seed with simple genes

Case 2: The design genes, in this case, are set almost the same as case 1.

gene4 = [Cross section, Circle, 1, 0.0, 1.5, 0]
gene7 = [Cross section, Square, 1, 0.0, 0.5, 1]

The only difference here is that 2 cross section types, "circle" and "square" are defined, each with different dominances and working conditions, as shown in the above gene4 and gene7. Based on the principle 4, 5 and 6, this seed can grow until step 4. Due to the dominance property, during the growth process, the "square" cross-section has priority to grow until Height = 1.0m, the cylinder ("circle" cross-section) then grow from Height > 1.0m until growth stops. Finally, a "non-uniform" structure is formed, as seen in Figure 3. It is found from this case that the gene's dominance plays a key role in emerging a design.

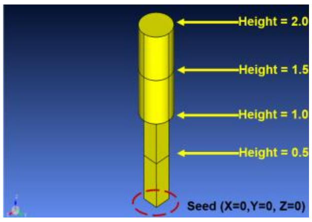


Figure 3. Dominance test

3. Practical design growth

Case 3: an example of a table-like structure growth is provided to verify the feasibility of the proposed system for practical design. The design genes are shown in Figure 4. A

"Gene group" is used here to aid the explanion due to numerous design genes in the seed. Gene group 1 defines 3 genes to form a cylider with length = 5mm ("Len" in row 2) and radius = 1mm ("Rad" in row 3) of circle cross-section ("CS" in row 1); their working conditions are all from $z \geq -40$mm to $z \leq 40$mm. $V_i = \boldsymbol{n}V_j$, where $X, Y, Z \in \boldsymbol{V}$; $\boldsymbol{n} = 1,2,\cdots,n$; $i, j = 1,2,3$ in first column in group 2 to 7 represents the vector conponent $V_i$of the *n*th growth direction, and its working conditions are closely related to value of V_j coordinate. Take the first 3 genes in group 2 as an example, they express a growth direction is verical (vector[0,0,1], see column 2 in each gene) which controled by working conditions $z \geq 0$mm and $z \leq 5$mm.

### Gene group 1	### Gene group 2	### Gene group 3	### Gene group 4	### Gene group 5	### Gene group 6	### Gene group 7
CS Circle 1 -40 40 1	X_1Z 0 1 0 5 1	X_2Z 1 1 8 10 1	X_3Z 0 1 3 20 1	X_4Z 0 1 8 10 1	X_5Z 0 1 3 20 1	X_6Z 0 1 3 20 1
Len 5 1 -40 40 1	Y_1Z 0 1 0 5 1	Y_2Z 0 1 8 10 1	Y_3Z 0 1 3 20 1	Y_4Z 1 1 8 10 1	Y_5Z 0 1 3 20 1	Y_6Z 0 1 3 20 1
Rad 1 1 -40 40 1	Z_1Z 1 1 0 5 1	Z_2Z 0 1 8 10 1	Z_3Z -1 1 3 20 1	Z_4Z 0 1 8 10 1	Z_5Z -1 1 3 20 1	Z_6Z -1 1 3 20 1
	X_1X 0 1 0 1 1	X_2X 1 1 0 15 1	X_3X 0 1 18 22 1	X_4X 0 1 0 20 1	X_5X 0 1 18 22 1	X_6X 0 1 0 1 1
	Y_1X 0 1 0 1 1	Y_2X 0 1 0 15 1	Y_3X 0 1 18 22 1	Y_4X 1 1 0 20 1	Y_5X 0 1 18 22 1	Y_6X 0 1 0 1 1
	Z_1X 1 1 0 1 1	Z_2X 0 1 0 15 1	Z_3X -1 1 18 22 1	Z_4X 0 1 0 20 1	Z_5X -1 1 18 22 1	Z_6X -1 1 0 1 1
	X_1Y 0 1 0 1 1	X_2Y 1 1 0 10 1	X_3Y 0 1 0 3 1	X_4Y 0 1 0 8 1	X_5Y 0 1 8 10 1	X_6Y 0 1 8 10 1
	Y_1Y 0 1 0 1 1	Y_2Y 0 1 0 10 1	Y_3Y 0 1 0 3 1	Y_4Y 1 1 0 8 1	Y_5Y 0 1 8 10 1	Y_6Y 0 1 8 10 1
	Z_1Y 1 1 0 1 1	Z_2Y 0 1 0 10 1	Z_3Y -1 1 0 3 1	Z_4Y 0 1 0 8 1	Z_5Y -1 1 8 10 1	Z_6Y -1 1 8 10 1

Figure 4. The design genes in the table-like structure seed

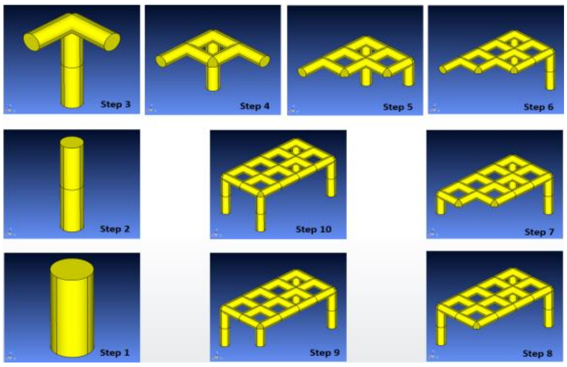
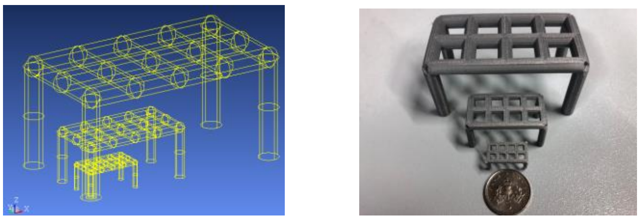


Figure 5. The structures in each growth step

Based on the growth algorithm presented in Section 2.3, a table-like structure is successfully grown until step 10 from the above seed. Figure 5 shows the history of the structure growth. It demonstrates the effectiveness of the proposed design system for emergence of complex practical designs.



(a) CAD models with different scales (4:2:1) (b) 3D printed structures (4:2:1)

Figure 6. CAD and 3D printed models of table-like structures

Figure 6 (a) shows table-like designs with different scales (4:2:1) emerge from the same seed in response to different environments (assume an environment that influences the final design). It illustrates the adaptability of the design genes. It is analogous to the events in nature whose seeds from the same plant can grow to become trees as disparate shapes with different mix of light, water and soil, etc. Figure 6 (b) shows the relevent printed table-like strucutres.

4. Discussions

In order to embrace design emergence using the present systerm, several things should be noted. Firstly, design genes play a crucial role in the growth of innovative designs. How to determine the reasonable value/type for each element in each gene requires further investigation. Secondly, this current system presents only a basic form of design genes, and the potential of a more generic solution approach opens many questions, such as dealing with variability and uncertainty, structural failure, growth strategies and so on. Thirdly, a simple growth rule without consideration of the environment is currently used during the growth process, but it is clear that the growth environment should have influence on the development of the design, as in nature.

5. Conclusions

A new fundamental concept in design has been formulated building a design growth system based on design genes which can reflect biogical growth strategies as seen in nature. Design genes have been defined which are simple triggers that direct the development of a design as it emerges. They can be packaged in a design seed to generate geometries, and can support rapid experimentation with shape to explore options and create opportunity for innovation. Effect of the growth environment on design genes and final designs are being considered in further work.

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