A Novel Design System for Exploiting Additive Manufacturing

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Abstract

Additive manufacturing (AM) is an example of a new process that is revolutionising manufacturing capabilities. This process offers the potential to create bespoke designs that are tailored to individual specifications without the burden of time or cost to manufacture that is attributed to customisation in manufacturing. However, when considering traditional design methodologies and the associated design systems and tools which operate in a 'top-down' sequential manner, the design space becomes constrained, and creativity limited. Additive manufacturing demonstrates the need for new thinking in design to open up the design space to create novel geometries that can capitalise on the new technology and its benefits. With this need comes new thinking with respect to design for additive manufacturing and design methodologies that have the flexibility to exploit these manufacturing capabilities. This work presents a novel design system created as a 'bottom-up' approach to design by exploiting nature and analogies with engineering. The system uses bio-inspired algorithms and entities to create geometries through a development process. This process is based on the rudiments of plant development, where a cell divides and grows in response to interactions with its environment through its own specific genetic code, the genome. In this system, the output from the system is the organism, a collection of 'geometric' cells, pertaining to concepts in cellular modelling allowing for parameters to be used as representation of design characteristics. External influences on the geometry of the cell, from its interaction with the environment are controlled and co-ordinated by hormones. The cells interact with its environment using sensors attuned to particular environmental influences (stimuli). Within the system, all cells have the same data structures, geometry, genome, hormone and sensors. External stimuli can come from expectations of performance aspects such as loading or from manufacturing capability.

This paper will describe the aspects of the system analogous to nature alongside the data structures used to represent the developing organism and its ability to interact and respond to the environment. It will demonstrate how manufacturing specific information can be coded in the system and in the genome of the cells and expressed in the organism through the development process in this new design system.

Key Words: Additive Manufacturing, Design, Bio-inspired

1. INTRODUCTION

1.1. Challenge of design for additive manufacturing

Additive manufacturing (AM) has developed rapidly to the point where it is capable of creating small scale bespoke parts or concept components to mainstream production parts. With continuing advancements it has been recognised that there are restrictions to the applicability of AM to certain parts and Thomson et al. (Thompson et al., 2016) show how current top-down design approaches cannot fully exploit AM. This is because top-down design reduces the problem into smaller segments, with constraints introduced that can prevent alternative manufacturing solutions becoming available. A more suitable approach suggested is bottom-up, where a solution can be built that supports AM. Achieving full integration between design and manufacturing processes is not a new concept. Price et al. (M. A. Price et al., 2013) recommend that parameterisation of the geometric model which represents the design should be tailored to the capability of the manufacturing process to maintain design intent so the operational product functions in service as intended.

1.2. Design innovation

Design innovation in the form of systems and frameworks used by industry has helped advance the diversity and number of products on the market. Systems engineering methods as a top-down approach using technology such as computer-aided design (CAD) and simulation tools throughout product development is an example. More

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recently tools such as TRIZ (Theory of Inventive Problem Solving) (Altshuller, 2005), set-based design (Ström, Raudberget, & Gustafsson, 2016), axiomatic design (Su, 2001) and generative design (Krish, 2011) have become prevalent. Generative design techniques are emerging as a highly functional tool for rapidly generating design concepts. One such example is topology optimisation (Bendsoe, 2004) which produces organic structures based on in-service simulations dealing with multi-disciplinary problems. This process is limiting, however, as it removes material from a pre-defined space and the resulting geometry requires post-processing to make it suitable to use in traditional software for further use in product development. These tools are powerful design tools focused on exploring designs at a concept phase but to support exploration of the full product development cycle including manufacturing processes, a new design process is required that is capable of adapting to and embedding detail as the design progresses.

1.3. Problem definition

The preceding sections identify (1) a need for an integrated approach to design modelling to ensure consistency in the parameter sets used in all phases of the design and manufacture and (2) an approach is required to go beyond the concept phase, with a toolset flexible enough to allow wide exploration from the beginning and be capable of adapting and embedding detail as the design progresses. This work proposes an approach which can address both of these by using bio-inspired metaphors to create a bottom-up design system that is more tightly integrated with the manufacturing environment.

2. LITERATURE REVIEW

2.1. Bottom-up generative design

Contrary to top-down design processes such as Systems Engineering, where the problem is decomposed and solved in a stepwise manner by designers, the bottom-up design process adopts a building block approach where each building block is studied in detail and all contributions are accounted for without constraints. In both cases, the assemblage of all sub-problems solves the whole, the difference being the nature of bottom-up design allows solutions to the problem to emerge. Constraints on the problem are not rigorously invoked allowing focus to be on capability and knowledge driving the design. In fact, a critical advantage from a design for manufacturing perspective, is that manufacturing process capability can be accounted for from concept onwards and design parameters directly influenced by or influencing manufacturing contribute to the formation of the solution.

Dimensional addition and detail insertion (DADI) (M. Price, Raghunathan, & Curran, 2006) is a concept that shows how a CAD model can accommodate an evolving design and enable links between simulation models representing the design. The representation is automatically generated from lower dimensional entities, such as sweeping points to create lines, which are swept to create surfaces and again to solids with the parametric relationships naturally evolving and remaining consistent as design continues. The prototype approach has the capability to build a fully defined CAD model of an aircraft fuselage. Simulation Intent (Nolan, Tierney, Armstrong, & Robinson, 2015) can be captured through cellular modelling and equivalencing maintaining links between the evolving regions of the CAD model. In other related work (Agarwal, Robinson, Armstrong, & Kapellos, 2018), in response to simulation results, local additional details have been added to a design using surface sensitivities to generate additional features and parameters on the CAD model. A challenge for this work is to explore this in the context of this integrated design and manufacturing environment.

2.2. Bio-inspired analogies for geometric modelling

2.2.1 Plant development

This work uses plant development as a metaphor to complement the DADI paradigm to support a bottom-up approach to design. Although still a subject of research, plant development provides general principles from which analogies have been extracted. The main aspects of plant development are cell growth and division. Growth includes primary growth (lengthening of the shoot) and secondary growth (thickening of the shoot).

Tropism, a specialised plant development process, is the response of the plant to stimuli in its environment. A common example is phototropism, where the plant will grow towards a light source, through cell elongation (by division or expansion) on the shaded side of the plant, Figure 1. Both growth and tropism mechanisms are controlled by the concentration and distribution of a hormone called auxin (Vanneste & Friml, 2009). Typically,

where auxin exists in high concentration, growth will occur. Although difficult to define, Leyser (Leyser, 1998) compares plant hormones to the animal nervous system which *'collects information from a variety of sources, processes it and directs appropriate response'*.
Fundamentally the phenotype (observable traits of the organism) is a result of its genetic code, which dictates certain characteristics, e.g., flower colour, combined with the influence of the environment on the expression of these genes. It is a combination of these three main concepts; development, hormones and genes that control the final form of the plant.

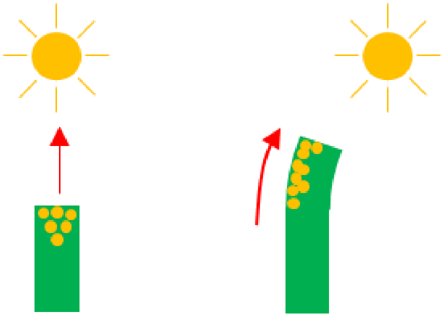


Figure 1 Phototropism in plants
The off-centre position of the light source triggers movement of auxin to the shaded side of the plant encouraging growth here(adapted from (Krogh, 2007)

2.2.2 Geometric modelling analogies

Useful analogies in geometric modelling systems for the plant development process are the concepts of non-manifold modelling and cellular modelling. Non-manifold representations (Weiler, 1988) (a face bounds more or less than one body, for example) are more common in simulation communities as they allow connection between different representations of a body (solid, shell, beam) to be maintained before, during and after analysis. Cellular modelling (Bidarra, Madeira, Neels, & Bronsvoort, 2005) is an alternative geometric modelling technique for analysis where the model is divided into sub-regions of geometric or simulation significance and are represented as 'cells' or individual bodies rather than a single body. Cellular models are non-manifold. These two concepts provide a means to represent plant development metaphors in an engineering design context. Cellular modelling supports cell-based plant growth where the final organism is a combination of sub-cells, and the development of each contributes to the final form of the organism. Non-manifold modelling is analogous to the plant being a collection of independent cells, that are, however, connected so the plant develops as a whole and is able to transport, for example, hormones during tropism to trigger developmental processes as described in Section 2.2.1. This means that in a non-manifold model, any changes to individual cells are propagated throughout the whole model, a key element of a bottom-up design process, where proximity of entities and emergence of interfaces are handled by the system rather than an individual.

Geometric parameters provide the analogy for the genes that control the characteristics of the model. Gero (Gero, 1998) used genes in architectural design where groups of fundamental elements were grouped as sets allowing facades to be extracted from population of designs, demonstrating the potential of genes to represent location and orientation of plans. This did not include complex representations for simulation or interaction with the environment as is the case in engineering applications.

Nolan et al. (Nolan et al., 2015) have demonstrated how enquiries on a cellular model and its parameters support automation of analysis tasks linking CAD and computer-aided engineering (CAE) systems, with Gero's work demonstrating the use of genes for design. The interaction between the model and its environment during development will complete the plant development analogy in engineering design.

3. BIOHAVIOUR SYSTEM

The following sections outline the data structures, the environment and product interaction with the environment which together form the Biohaviour system.

3.1. Data Structures

3.1.1 Geometry

The geometry data structure contains the information to describe the shape and form of the cell. This DADI approach allows for simpler representation of the cell region in 3D space, but a more typical B-Rep (boundary representation) structure of vertices, edges and faces can be encoded to link directly with commercial CAD systems for enhanced functionality.

3.1.2 Genome

The genome structure contains the information that will allow for expression of the final form and shape of the cells and ultimately the organism. This 'genetic' information is stored in the form of design genes (Zhang, 2019) where a single gene is the basic functional unit of heredity dictating how a cell will express a given characteristic. In this system, the genes define key characteristics such as parameters for length, cross-section, material or failure stress. The totality of the genes forms the genome, however, in any one genotype only a subset of the genome is active to express characteristics. The gene is structure is described more fully in Zhang (Zhang, 2019).

3.1.3 Hormone

The hormone structure holds the data that determines the expression of genetic attributes. The expression of an attribute and the magnitude of this expression is determined through the presence and concentration of hormone. It is simply an integer data type that triggers the expression of a gene using the upper and lower limits of that gene.

3.1.4 Sensors

Sensors are a data structure that provide the interface between the cells and the environment. They exist in the cells and connect through complementary data types with stimuli in the environment to trigger a hormonal response in the cell. A sensor has two components, the receptor which receives the stimulus information before sending it to the second component, a convertor which converts the receptor data to a hormone supplement that is passed to the cell for future development processes, such as growing in length.

3.2. Development

Development consists of three individual cell-level processes: growth, division and budding. This creates branching plant-like structures within the system, although, the process is general and can apply to solid and shell structures. Branching structures are long and thin and grow along the main axis which is termed as primary cell growth. Increases in the cross-section (width) of these structures is termed as secondary growth which is a direct response to internal stresses. Division occurs at the end face of the cell, where a zero-volume cell is created and inherits the genome from its parent cell. Budding is a form of division, where the zero-volume cell is created on the long face of the cell. This new cell inherits its parent's genome and grows laterally to its parent cell. An example of a structure grown in this way is shown in Figure 2

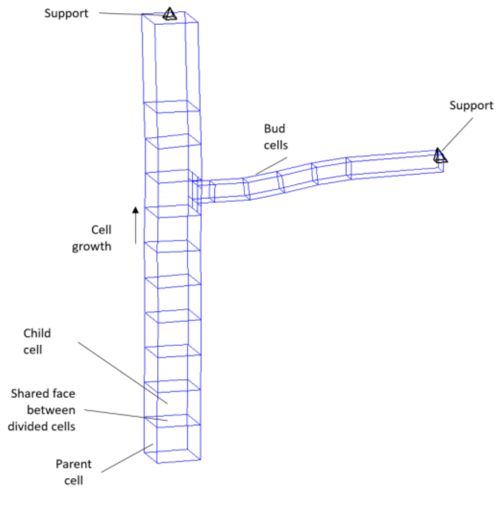


Figure 2 A developed organism showing cell growth, division and budding

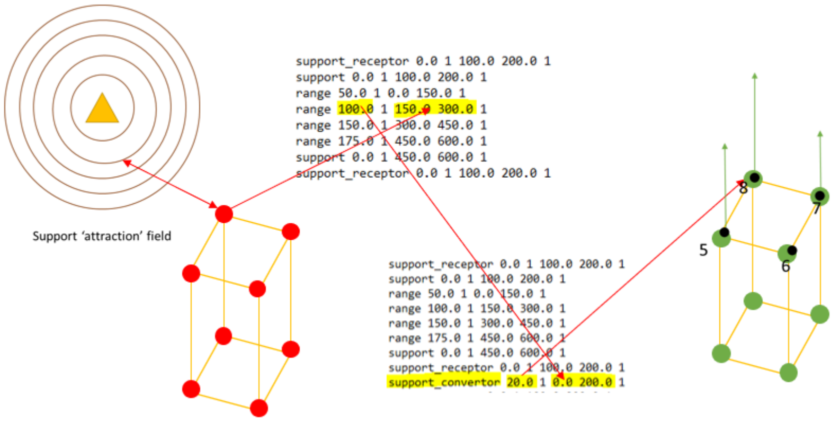
3.3. The environment

3.3.1 Representation

The environment exists to influence the development of the organism, just as tropism is seen in plants, Section 2.2.1. The environment in our engineering context contains two ‘types’ of stimuli. Primary stimuli are attractors, repellers or exclusion zones which have a direct effect on the shape and form of the organism. Secondary stimuli represent typical boundary conditions such as loads and constraints and when linked to simulation results these will cause a change in the internal state of the organism. Both these stimulus types invoke a hormonal response in the organism, the magnitude and effect of which is controlled by the sensors (ultimately the genetic code).

3.3.2 Interaction

The interaction between the organism and the environment is facilitated by the sensors. As stated in section 3.1.4, complementary sensors exist for each stimulus in the environment. The cell uses its sensors to scan the environment for its complementary stimulus, and if multiple exist, the cell will aggregate the hormone effect of each stimulus on its vertices before proceeding with development. Figure 3 shows how cell receptors (red) read the field strength of the support stimulus, use the range gene’s start and stop parameters (Section 3.1.2) to pass the corresponding delta parameter to the convertor (green) where a proportion of the delta value (hormone supplement) is directed to the vertex to facilitate growth in the cell during development. This hormonal response to the stimulus affects the form of the cell, hence the organism is developing in response to its environment.



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support_receptor 0.0 1 100.0 200.0 1
support 0.0 1 100.0 200.0 1
range 50.0 1 0.0 150.0 1
range 100.0 1 150.0 300.0 1
range 150.0 1 300.0 450.0 1
range 175.0 1 450.0 600.0 1
support 0.0 1 450.0 600.0 1
support_receptor 0.0 1 100.0 200.0 1
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support_receptor 0.0 1 100.0 200.0 1
support 0.0 1 100.0 200.0 1
range 50.0 1 0.0 150.0 1
range 100.0 1 150.0 300.0 1
range 150.0 1 300.0 450.0 1
range 175.0 1 450.0 600.0 1
support 0.0 1 450.0 600.0 1
support_receptor 0.0 1 100.0 200.0 1
support_convertor 20.0 1 0.0 200.0 1
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Figure 3 Environment interaction via the cell sensors

4. DESIGN FOR ADDITIVE MANUFACTURING

To illustrate how this approach can accommodate manufacturing capability, one of the critical design conditions that contributes to a successful additive manufactured part is considered. This condition is the aspect ratio (AR), the ratio of feature height to feature width. The maximum limit is process specific but if exceeded the feature will require supports in the model to prevent deformations. This increases costs, time to manufacture and will require post-processing to remove support materials. This example demonstrates how this design system can detect and respond to specific manufacturing conditions using an environment stimulus and a genetic response.

4.1. System setup

4.1.1 Environment

Manufacturing specific information is included in the system through a manufacturing stimulus as part of the environment, Figure 4. In this example, the process is Direct Metal Laser Sintering (DMLS), with maximum aspect ratio of 8. Stimulus format (similar to genes) allows inclusion of other process specific information, such as maximum wall thickness, not included for this example.

[manufacturing, additive, DMLS, 0.25, 7, 8]

Figure 4 Additive manufacturing stimulus

4.1.2 Genome

As described in Section 3.1.4, complementary sensors to the 'AM' stimulus will support interaction between the stimulus and the organism. An 'AM' sensor included in the genome will detect the process aspect ratio from the stimulus and by comparing with the current state of the organism, i.e., its aspect ratio, compare and convert the received information to a hormone supplement triggering future development if necessary.

4.2. Results

Figure 5 shows a developing organism with an aspect ratio of 9.85 which the sensors detect is greater than the aspect ratio of the manufacturing stimulus. The sensors respond by sending a hormone supplement to the vertices of the cells (highlighted in red) in the x-y direction (green arrows) Figure 5. This supplement is proportional to the ratio of the stimulus AR and the organism AR (0.812). The higher the ratio, the higher the hormone supplement to increase 'thickness' and reduce the organism AR to within the manufacturing stimulus range. In this example the development continues with the hormone supplement increasing the 'thickness' of the organism, Figure 6, resulting in a new organism AR of 6.35, within the manufacturing stimulus limit.

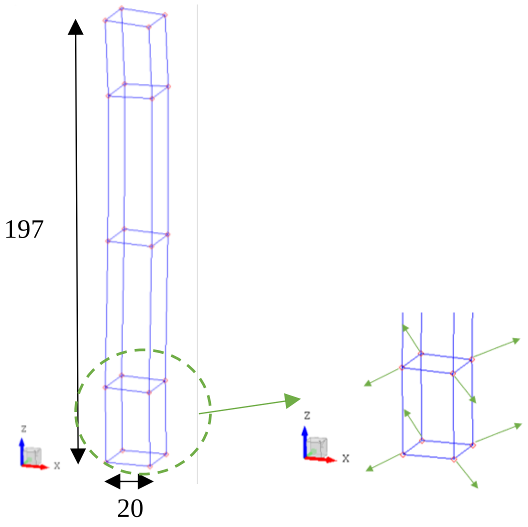

Figure 5 Organism with AR of 9.85

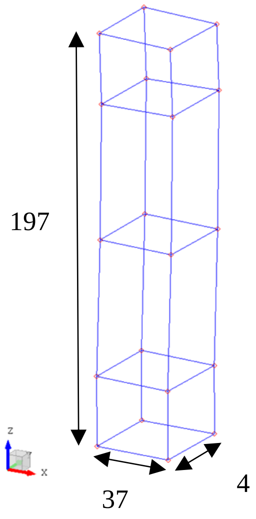

Figure 6 Organism post manufacturing sensor response

Figure 7 shows a variety of bracket shapes which developed from the same genome, small perturbations in individual genes or the environment allow variation to flourish, and with the approach so responsive to the manufacturing environment there is significant potential to tailor designs to the manufacturing capability.

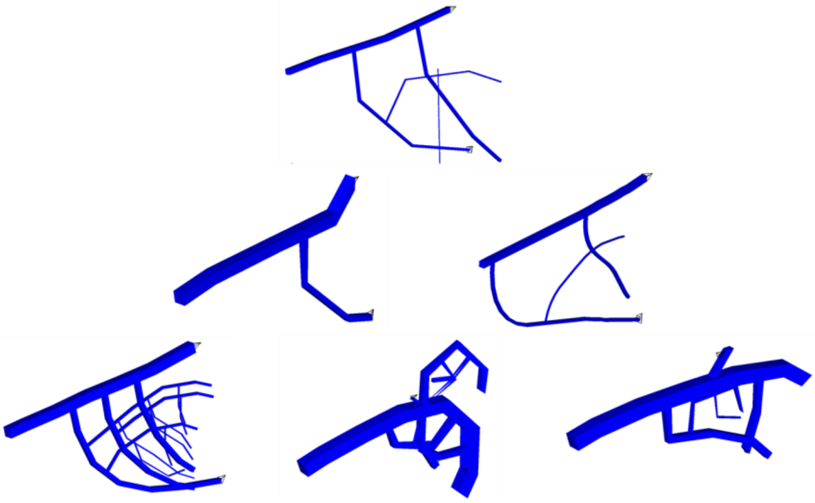

Figure 7 Selection of brackets developed from slight genetic changes in the genome

5. DISCUSSION

This paper has demonstrated a new design system that can take account of the capability of novel manufacturing systems. Having identified (1) the need for an integrated approach to design modelling used in all phases of design and manufacture and (2) a flexible toolset supporting design innovation that can go beyond the concept phase, we have presented a new bio-inspired system in which nature inspired metaphors have informed design analogies. Three key outcomes of the design system are:

- Changing genome and genes (genotype) can result in an array of possible phenotypes (organisms) opening up the potential for innovation in solutions.
- The geometry changes in response to its environment, described in Section 3.3 and demonstrated in Section 4. The system is dynamic and agile.
- The environment can be built from many stimuli which each affect the developing organism differently, e.g., in Section 4, a manufacturing process that alters geometric form to ensure manufacturability.

The example in Section 4 has shown the capability of the system to integrate manufacturing directly with design. The environment within which the organism develops was extended to include specific manufacturing information related to an additive manufacturing process. Using the sensor-environment interaction, Section 3.3.2, the organism responded by altering its geometry to account for process specific conditions. Although showing one step in the development process for understanding, the organism-environment interaction continues throughout development constantly checking and adjusting to manufacturing conditions ensuring these considerations also drive the design process. This highly novel approach has major potential in bringing manufacturing considerations at an earlier point in design and tailoring it to the manufacturing environment.

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