Parasitic Ecologies

Algorithmic Space through Diffusion-Limited Aggregation of Truncated Octahedrons

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Parasitic architecture allows the creation of flexible structures that feed off existing infrastructure. Additionally, self-organised models that grow in response to environmental forces and adapt to their context introduce new ways for intervening in architectural design. This paper investigates the properties of self-organised parasitic structures that evolve by creating aggregation forms in the context of simulated structural environments. The growth process of the parasitic structures is inspired by the fungal colonies and is based on the rules of diffusion-limited aggregation (DLA) extended to support real-time force analysis and aggregation of space-filling geometry. The results of the simulations demonstrate that the developed diffusion-limited aggregation of truncated octahedrons is capable of providing self-sustained structures able to adapt in environments with different spatial limitations.

Keywords: *Adaptive Structural Models, Parasitic Architecture, Diffusion-Limited Aggregation, Self-organisation, Java*

INTRODUCTION

Buildings are massive, permanent and static, and therefore often unable to deal with the amount of energy embodied in their structure. Yet the 20th century has seen the emergence of structural models that use nature as the generating force for their form. Similarly, living organisms that grow under specific environmental conditions and adapt to their context after a series of evolution iterations interact and evolve in harmony with natural forces. This approach, which demands combined effort of architecture, biology, and computer science, focuses on the generative process of the structure and ensures the creation of models that are balanced with their context.

Based on ecological relations found in nature and in particular in fungal parasitic colonies, this paper explores the idea of using spatial diffusion limited aggregation of space-filling polyhedrons for the emergence of self-organised structures. In order to establish the foundation for our research a high performance real-time analysis software was developed and a spatial diffusion limited aggregation algorithm was designed.

The significance of this new spatial diffusion limited aggregation algorithm is that it reimagines the biological analogies in relation to real-time adaptive structural models in architectural design. In particular, we investigate, through a series of simulations, the evolution of self-sustained parasitic structural models that evolve by creating aggregation forms in the context of simulated structural environments. Throughout the evolution the structural integrity of the model is tested in real-time to ensure that all major structural integrity factors meet the requirements.

TOWARDS BIOLOGICAL ANALOGIES

The impact of biological models on architecture resulted in new ways for intervening in design. Thomson (1942) was one of the first researchers, who addressed, the interrelation between growth and form. In his study, the form of organisms is considered as an event in space over time rather than a spatial configuration meaning that the growth process is the basis for the resulted form. Drawing on the same discipline, more recently, Ball (1999) explored pattern formation in nature suggesting that all the forms that appear can be considered as results of specific growth processes. As Steadman (2008) argues in an attempt to introduce growth process into architectural design, during development there should be a frequent interaction between the growing design and its environment. Steadman's assumption can be considered as derivation from Lamarck's theory of adaptation, in which an organism-system grows in response to environmental forces but also influences its environment correspondingly (Gould, 2002).

Studying and interpreting biological analogies in relation to architectural design allows the development of emergent and self-organised structures. Emergent structures are the complex systems that arise from relatively simple interactions while self-organisation refers to the ability of a system to adapt in a continually changing environment (Camazine et al., 2003).

PARASITISM - AN ECOLOGICAL RELATION

The term Parasitic Architecture refers to flexible and temporary structures that feed off existing infrastructure (Allen et al., 2003). This idea has received considerable attention from architects, who envisioned architecture not as a permanent space for humans to live in, but as a motivation for social engagement, freedom and endless transportation. Constant Nieuwenhuys was one of the first architects that addressed the mobility of architecture (1964/2001) with his proposal of the New Babylon in 1959-74.

In biology, the term parasitism refers to an ecological relationship (Bush et al., 2001) between two organisms, where one organism, the parasite, takes advantage of its host. Half of all species of organisms are parasites, which create a continuum of interactions between species that negotiates natural equilibrium. Among the great diversity of parasitic species, a class that presents significant importance is this of fungi. Fungi are modular organisms (Carrol and Wicklow, 1992), meaning that they grow by repeated iterations of parts called modules. In a fungal colony the module is a thin, tubular structure called hyphae that extends and presents apical characteristics of growth (Moore, 1998). Fungal modular growth leads to a root-like form (Gow and Gadd, 1995) called mycelium that exhibits great plasticity, complexity and diversity. The mycelium extends over or through whatever substrate the fungus is using as a source of food. Although, their growth mechanisms are of primitive intelligence, they allow for the creation of complicated networks that can be considered as three-dimensional lattices (Figure 1).

Figure 1
Fungi and fungal mycelium (source: http://en.wikipedia.org/)

GROWING FRACTAL FORMS - DIFFUSION LIMITED AGGREGATION

The growth process of fungi is influenced by non-local factors such as shadowing, temperature and humidity conditions. These far from equilibrium growth phenomena, in which diffusing particles are added to a growing aggregate, can be studied by approaches based on diffusion-limited aggregation (DLA). DLA was proposed by Witten and Sander (1981) in order to simulate the formation of clusters by particles diffusing through a medium that collides the particles with each other as they move.

The growth rule of DLA is remarkably simple. First, an immobile seed is located on a planar surface. A walker is then launched from a random position far away and is allowed to diffuse (walk at random). If it touches the seed, it is immobilised instantly and becomes part of the aggregate. Then similar walkers are launched one-by-one and each of them stops upon hitting the cluster. After launching a few hundred particles, a cluster with intricate branch structures results. The resulted fractals have a randomly branching open structure and look stochastically self-similar (Figure 2).

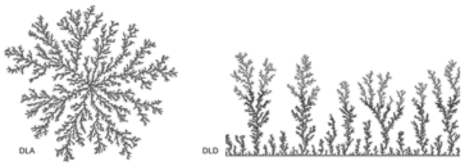

Figure 2
Left - Simulation of Diffusion Limited Aggregation (DLA).
Right - Simulation of Diffusion Limited Deposition (DLD).
(source: http://en.wikipedia.org/)

There are several growth models that are presented as extensions of the DLA method. Diffusion Limited Deposition (DLD) (Meakin, 1983; Rácz and Vicsek, 1983) is very similar to DLA but the single seed is replaced by a surface to which diffusing particles are attached. The presence of the surface allows for more complicated systems to emerge. The forest of clusters shown at figure 2 is a typical example of DLD. Another extension of DLA is Ballistic Aggregation (Ramanlal and Sander, 1985). During Ballistic Aggregation (BA) the particles move along straight lines until they encounter the aggregate and stick to it.

DLA through a simple implementation provides a wealth of behaviour and a basis for interpreting a large range of natural pattern formation phenomena. There is a wealth of research on DLA usually in two dimensions on models of fractal growth processes such as river networks, plant branching, frost on glass, electro-deposition, lightning, mineral deposits, and coral. However, DLA is a rather unexplored field in architecture and there is a lack of knowledge with regards to the forms that emerge through DLA of space-filling geometry.

AIMS AND OBJECTIVES

The aim of this paper is to address the generation of parasitic structures, which evolve by creating aggregation forms in the context of simulated structural environments. The adaptation of a new generated system into the existing built environment allows the examination of space extensions and the emergence of new spatial patterns. To develop a new space within or upon an existing structure requires a strategy that provides a method to maintain an attachment and structural integrity.

The main objective is to simulate the growth of a parasite in a three-dimensional model in respect to some of the rules that are applied to fungal colonies. For this study, the module, which replicates the fungal hyphae, is expressed with the use of a space-filling polyhedron, the truncated octahedron. Space-filling polyhedrons allow for space tessellation and also exhibit great structural stability. The space-filling polyhedrons are aggregated based on the DLA growth algorithm and the emerging form is continuously tested for its structural integrity.

To explore the adaptive growth of parasitic and self-sustained modular structures, we developed a high performance real-time simulation and analysis software built in Java. This was then used to examine:

- the efficiency of the Spatial Diffusion-Limited Aggregation developed for this study,
- the structural integrity of the evolving model

through a real-time analysis of all major structural integrity factors,

- and its growth and adaptation within existing spatial setting.

Additionally, we developed Ballistic Aggregation (BA) and Diffusion Limited Deposition (DLD) spatial implementations in order to strengthen our observations and compare our findings.

DIFFUSION LIMITED AGGREGATION OF TRUNCATED OCTAHEDRONS

A truncated octahedron is an Archimedean, space-filling polyhedron with 24 vertices, 36 edges, and 14 faces. In a truncated polyhedron, all edges are of the same length and eight of its faces are regular hexagons while the other six are squares. The ability of the truncated octahedron module to attach to either a square or hexagonal face results in a large number of unique configurations. The truncated octahedron is the simplest and the most economical in terms of surface area-to-volume ratio of the space filling systems (Pearce, 1978) and the triangulations that are formed within a space filled with truncated octahedrons allows a high degree of stability and an equal transfer of the compressive forces.

The aggregation of truncated octahedrons followed the basic growth rule of DLA. In order to aggregate the polyhedron, each particle was considered to transfer a virtual truncated octahedron around it. During the attachment process a face-alignment algorithm was employed. The walker was searching randomly in a sphere around the seed particle and it could become part of the aggregate if it had the appropriate distance. To attach the polyhedrons with aligned square faces the distance between the particles should be greater or equal to two times the distance of the centroid of the polyhedron to the centre of its square face (square radius) and to acquire adjacent hexagon faces the distance should be greater or equal to two times the distance of the centroid to the centre of the hexagonal faces (hexagonal radius). Figure 3 shows the two different cases.

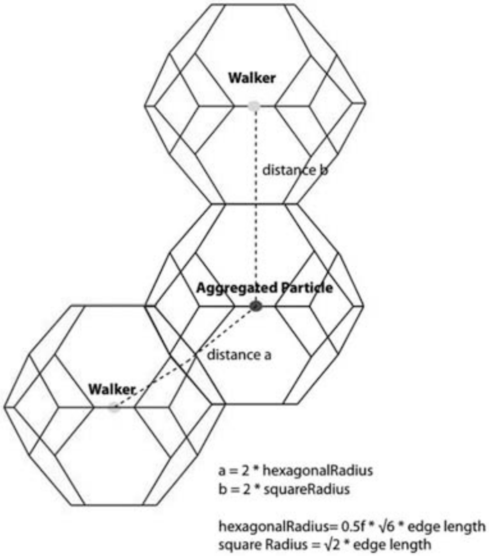

Figure 3
Diffusion-Limited Aggregation: Diagram showing the alignment of truncated octahedrons

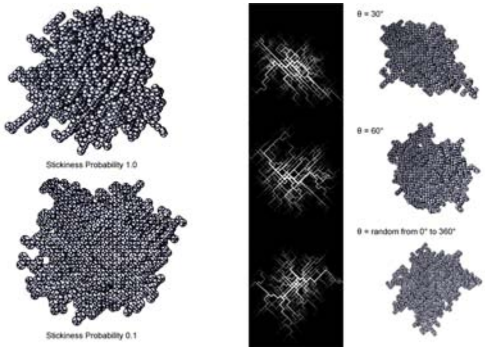

Figure 4
Diffusion-Limited Aggregation of Truncated Octahedrons: Left - Simulations with different stickiness probability values. Right - Simulations showing the effect of applying different angles to the direction of walker (up: angle=30°, middle: angle=60°, bottom: angle=random 0° to 360°)

To control the density of the structure, a probability of adhesion (stickiness) was also introduced. Additionally, a constraint for controlling the direction of the growing model by restricting the path of the random walker to specific angles was implemented. Figure 4 shows how the stickiness probability and the direction of the walker affect the density and form of DLA of truncated octahedrons.

STRUCTURAL ANALYSIS AND OPTIMISATION

Once the constraints of the aggregation were set, the next step was to calculate the forces within the system. As discussed, the triangulations that are formed within a space filled with truncated octahedrons allows a high degree of stability and an equal transfer of the compressive forces. The analysis focused on the weight of the structure and the moment of force that is produced as a result of it. Each shape consisted of 36 tubes that connected the vertices of the truncated polyhedrons. The weight of each branch of the aggregation was defined as a vector that started from the centroid and was perpendicular to the XZ plane with a magnitude equal to the mass (volume * density) of the branch. In fact, the weight of each branch is the force on the branch due to gravity and its magnitude is the product of the mass of the branch and the magnitude of the local gravitational acceleration W=mg but because the gravitational acceleration was equal for all the branches it was set to 1.0 m/s^3.

The calculations covered two phases: the first was about the moment of force applied to a specific joint of the structure from the weight of the whole structure above it; and the second focused on the transfer of compressive forces within the structure and the moment of force applied to each joint. For the first phase, as the moment of force is the cross product of the lever-arm distance vector and the force vector (in this case the weight), which tends to produce rotation, the aim was to calculate the centre of mass of the structure and the distance between the centre of mass and the joint that was about to be tested (Figure 5).

To calculate the compressive forces within the structure, the weight vector of each branch was resolved into a vector along the axis of the branch and a vector perpendicular to the branch's axis. The vector along the axis transfers the compressive force through the structure, while the perpendicular force vector is responsible for the moment of force at each joint. Figure 6 shows the analysis that was followed for a set of branches. To define the compressive force, the dot product of the weight vector and a normalised vector with a direction from the centre of mass of the branch to its starting point were also calculated.

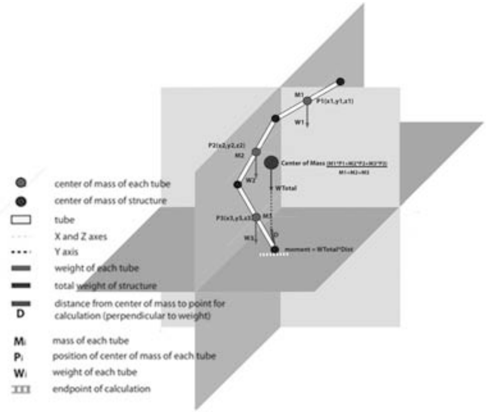

Figure 5
Structural Analysis: Diagram showing the calculation of the centre of mass

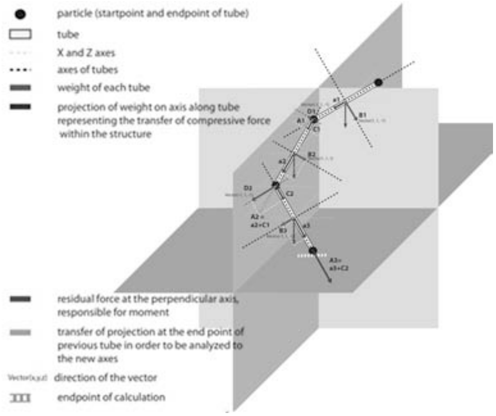

Figure 6
Structural Analysis: Diagram showing the transfer of forces within the structure

As moving from joint to joint apart from the compressive force that was generated from the weight of the current branch, the previous calculated force vector was also resolved into its new components. The perpendicular to the axis of the branch force components were added at each joint and provided a moment of force at a specific direction while the compressive forces were added separately.

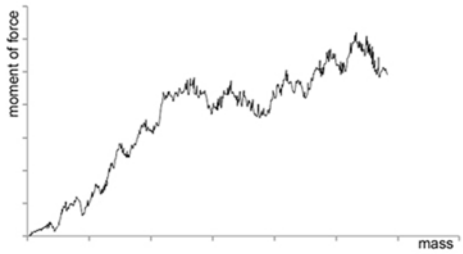

Figure 7
Plot showing the relation between mass and moment of force during the evolution of a DLA of truncated octahedrons.

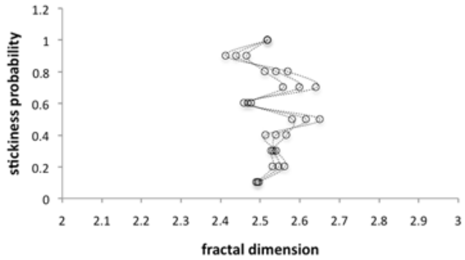

Figure 8
Plot showing the relation of fractal dimension and stickiness probability for three-dimensional DLA with truncated octahedrons

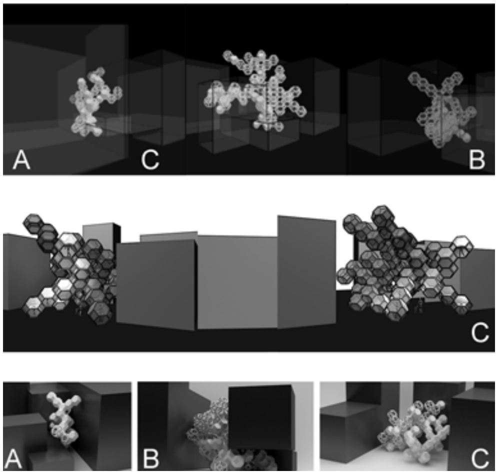

Figure 9
Adaptation: Self-sustained DLA of truncated octahedrons grown in highly restrictive (A), semi-restrictive (B) simulated environments and in open space (C)

The diameter of the tubes of each truncated octahedron was at first set to an initial size. If a new truncated octahedron was attached to a branch, the diameter of the tubes of the existing polyhedrons that extend to the root would recursively increase in size. By increasing the diameter of the tubes, the capacity of the structure to withstand compressive forces was optimised. When a new truncated octahedron became part of the aggregate, the moment of force was calculated. If the moment of force exceeded a predefined threshold then the new truncated octahedron was removed from the branch and a new walker was released. The plotted data of mass and moment of force for a DLA of truncated octahedrons (Figure 7) depicts the pattern of evolution.

EFFICIENCY - STRUCTURAL INTEGRITY - ADAPTATION

After a number of aggregated polyhedrons, each structure reached equilibrium. The total number of the aggregated polyhedrons was dependent on the maximum moment of force that the structure could afford as well as to the stickiness probability. The denser the structure was, the more stable it proved to be.

The results of the simulations revealed that the DLA of space-filling polyhedrons maintains the characteristics of a typical DLA model in three-dimensions. In typical three-dimensional DLA models with stickiness probability, the fractal dimension can take values equal to 2.50 ± 0.15 (Vicsek, 1992). Figure 8 shows the relation between fractal dimension and stickiness probability for self-sustained three-dimensional DLA of truncated octahedrons. The aggregates of truncated octahedrons that grew based on Diffusion-Limited Deposition algorithm proved to have a fractal dimension within the same range.

Furthermore, the introduction of the multivariant real-time structural analysis succeeded in forming a self-organised structure that reaches equilibrium in response to its context (Figure 9). The findings of the analysis on the stability of the structure

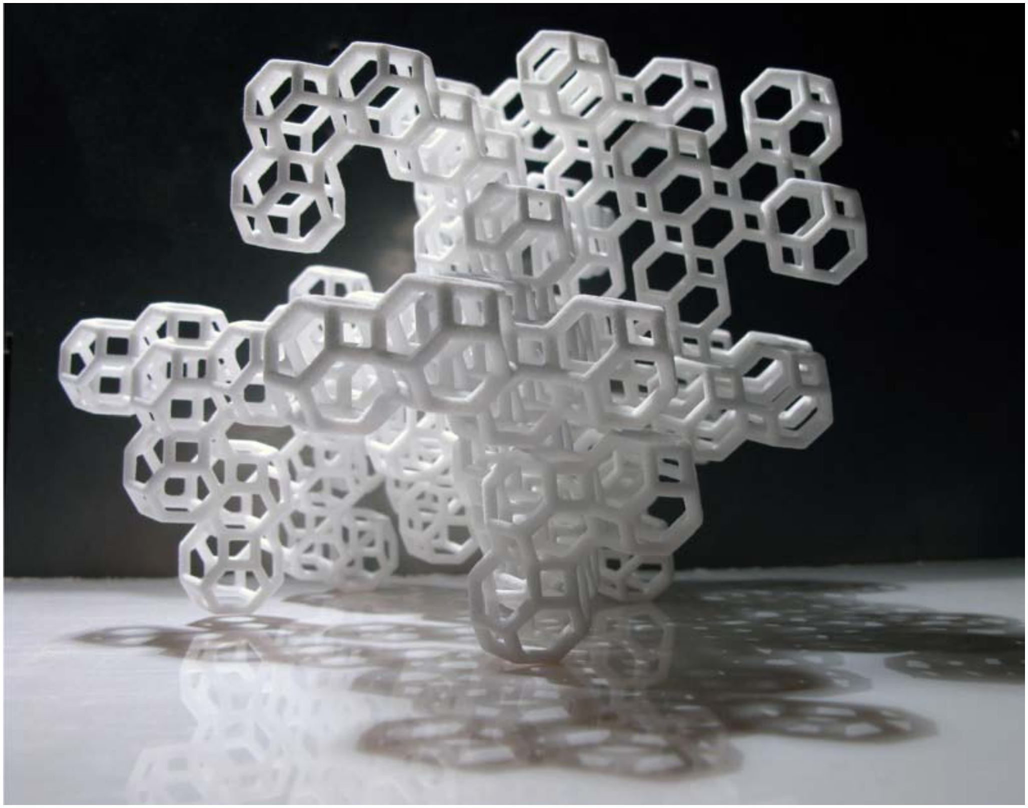

Figure 10
Diffusion-Limited Aggregation of truncated octahedrons - Rapid Prototyping Model

demonstrate that diffusion-limited method (DLA) produces more balanced structures than the ballistic method (BA). Examining the relation of mass and moment of force during the evolutionary process further strengthened this finding.

Finally, it was shown that the structure was able to adapt over time in all different simulated structural environments in accordance with the constraints that were applied such as the direction of growth and the density of the existing context. Figure 9 shows examples of the model grown in different environments.

CONCLUSION

This paper has addressed the development of self-sustained parasitic structures that evolve by creating aggregation forms in the context of simulated structural environments through a new spatial diffusion-limited aggregation algorithm and software. It involved the biological paradigm of fungal colonies, which adapt to the changing environmental conditions providing a meaningful example of ecological relations such as parasitism, in nature.

The methodology followed was based on a new three-dimensional DLA algorithm extended to include a multi-variant real-time structural analysis and also to allow the aggregation of space filling geometry. The DLA of truncated octahedrons (Figure 10) proved to have the same fractal dimension with a typical three-dimensional DLA model. During the structural analysis, extensions of the DLA (diffusion-limited deposition and ballistic aggregation) were also studied and compared as an attempt to optimise solutions. The results of the simulations showed that the diffusion-limited method is more capable for providing self-sustained and well balanced structures than the ballistic method. By conducting a series of simulations, the capacity of the algorithm was proved successful in developing self-organised and self-sustained structures able to adapt in areas with different spatial limitations.

Although, the introduction and repetition of space-filling polyhedrons offers the potential for production and assembly in human scale and creates opportunities for flexible and temporary parasitic structures within existing infrastructure, to adopt such a strategy in real-world scenarios requires further experimentation in urban settings and specification of materials. It is also essential to examine diffusion-limited aggregation of different polyhedrons and compare their structural efficiency and adaptation capability.

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