Cooperative Trees by Adding Inosculated and Discrete Definitions to a DLA Design

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This paper presents a method to generate free-form branched structures from a small number of different constructive elements, based on the postulates of discrete or combinatorial design. The research is based on the study of fractal growth as a generator of complex tree-like structures, using references from other scientific approaches in which the possibilities of the DLA (diffusion-limited aggregation) model have been explored. The proposed method uses the Grasshopper visual programming language, and incorporates new topological strategies to improve the performance or robustness of the system through tree-tree (inosculation) and tree-soil (aerial roots) cooperations. The simulation demonstrates the effectiveness of the proposed method and its potential for the construction of structures with complex geometries from a discrete set of knots and bars and bioinspired strategies. The paper includes a review of the chosen design principles, the developed methodology and a recent physical test in Medellín (Colombia).

Keywords: *DLA, discrete design, inosculation, branching structures, virtual-real models*

INTRODUCTION

This paper focuses on applying discrete or combinatorial design to structures, based on the understanding that this is desirable in constructive terms. The objective of this work is to develop a method to design free-form branching structures based on a limited number of different knots and bars of the same length.

FREE-FORM TO DISCRETE-FORM BRANCHING DESIGN

Fractal growth by diffusion-limited aggregation (DLA)

In recent years, the development of computer simulation tools has generated various lines of research that explore how fractals can be used as design tools, applying them to different scenarios. Fractals are widely present in nature and we can learn from them to reproduce growth patterns. Their complexity, however, requires a bottom-up approach: the properties of simple objects need to be defined so they turn into complex objects when assembled (Kautz and Shutters 2011). For example, Greenberg (2008) describes two main optimization strategies in natural branched structures: on the one hand, the "logic of the bifurcation angle" tries to consider the constant angular range in which transfer of fluids and loads are effective to avoid turbulences; on the other hand, the "phyllotactic logic", a distribution of branches following a spiral pattern to maximize solar exposure avoiding self-shadows.

One of the most studied models for generating fractal structures is diffusion-limited aggregation (DLA), proposed by Witten and Sander (1983). This model describes the formation of clusters when particles in motion collide with other particles that remain fixed (see Figure 1). In architecture, DLA has been mainly applied to the study of urban growth (Batty et al. 1989) (Chan and Chiu, 2000). Other works have addressed smaller scale problems, using the DLA to design spaces according to environmental considerations such as sunlight (Kim and Lee 2015) or the interaction between people and their roles within a company (Sun et al. 2015).

Diffusion-limited aggregation has also been used to design structures. Previous work has explored its potential as a tool to model the morphology of plants and algae (Serrano et al. 2017). Other studies, such as Busch et al. (2011), propose a modular material system in which the aggregate particles are assimilated to discrete elements that come together to form an emergent structure. In the same line, Kachri and Hanna (2014) propose a system in which the structure is formed by the merger of octahedrons truncated on their faces, which is then analysed and structurally optimised. Narahara (2009) also incorporates structural evaluation into the DLA model, through physical simulations of the equilibrium of the generated clusters.

Combinatorial Design

Systems that correspond to the definition of combinatorial design are described in the works of both Busch (2011) and Kachri and Hanna (2014). Busch et al. (2011) clearly describes the stages the algorithm must solve: attraction, particle fixation, alignment and random rotation, all of which are necessary to generate an unpredictable configuration (see Figure 2).

For Sánchez (2016), combinatorial design in architecture embraces strategies based on the permutation and repetition of discrete units of material. In a similar way, Borhani and Kalantar (2017) highlight the relevance of a new constructive language in which the geometry of discrete structural elements allows to assemble them through interlocking. Retsin (2016) points out the advantages of discrete assembled systems, highlighting the automation capacity of these constructive processes through the serialization of actions. Dierichs and Menges (2013) propose a set of aggregation rules that, as in the DLA, are based on kinetics and collision to build a structure from discrete elements. This paper focuses on applying combinatorial design to structures, based on the understanding that this is desirable in constructive terms. The objective of this work is to develop a method to design free-form branching structures based on a limited number of different nodes and bars of the same length.

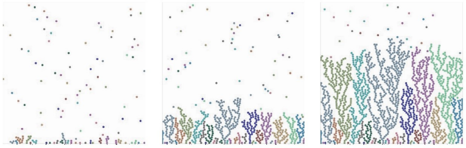

Figure 1
The NetLogo "DLA Alternate Linear" model: a variation of the original DLA model [1].

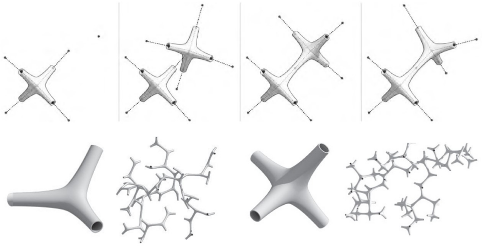

Figure 2
Aggregation of discrete units proposed by Busch (2011).

New topology strategies: inosculation and aerial roots

Literature on the relationship between growth, shape and stability in plants is extensive. Mattheck (1998) described how the strategies developed by trees to avoid collapsing can inspire the design of structures. Some tree species such as redwoods are capable of self-grafting, that is, their branches can be reattached to the trunk creating a buttress that helps the tree to resist wind loads more efficiently, as suggested by Preston [2]. This phenomenon is called inosculation and can also occur between different individual trees, thus leading to structural collaboration (see Figure 3). On another scale, the reconnection of diverging branches is called anastomosis. An example is the reticulate venation observed in the leaves of some tree species. Laguna (2008) suggested that the veins that separate and rejoin are more abundant in the areas of the leaf that are subjected to greater structural stress due to the leaf's weight. Klemmt (2014) compared the advantage of reticular venation patterns (with anastomosis) versus dendritic venation patterns (without anastomosis) such as DLA clusters, in terms of mechanical stability.

Figure 3
Examples of trees with inosculated branches [3,4,5].

Figure 4
Tree of the Ficus genus in Alicante (Spain).

The development of aerial roots is another strategy used by some tree species to increase their stability (see Figure 4). When the aerial roots of Banyan trees and other types of ficus trees touch the ground, they can merge and form pseudo woody trunks that allow horizontal branches to reach great lengths and a large overall tree size (Jackson 1986).

Inosculation and aerial roots can be interpreted as topological strategies that increase the stability of branch structures, in which constantly diverging elements result in the appearance of significant deformations when submitted to loads. The method presented in this study puts forward some geometric procedures to incorporate these strategies into the DLA model.

MODEL ASSEMBLY

Particles

The Grasshopper visual programming tool, part of the Rhinoceros software, was used to implement a recursive routine. The proposed model was based on the NetLogo "DLA Alternate Linear" model [1], transferring it into a three-dimensional version. The system's rules are defined below:

- Moving particles arose in random positions in the upper face of the prism in which the simulation space was enclosed. They followed a vertical downward trajectory covering the same distance at each iteration, so they maintained a constant falling speed.
- The particles in motion could be added to the first capturing particles that remained fixed on the floor of the simulation space. If they did not succeed, they passed by and were discarded.
- The particles that were captured became part of the cluster and became capturing particles.

Knots

As a criterion to homogenise the structural elements, the number of joints between bars was proposed to be reduced to 3 (see Figure 5). The first of them (knot

A) corresponded to the first capturing particles located on the ground and was the starting piece of the structure. The second (knot B) corresponded to the bifurcations resulting from the aggregation of particles, and was conditioned to continually form the same angle. The last connecting piece (knot C) connected the branches with the bridges (inosculation) and with the pseudo trunks (aerial roots). The knot shapes approximated the smooth transitions between tree branches as described by Mattheck (1989). The structure's bars had a circular section. The length of bars arising from the aggregation of particles had a single fixed size. The bars appearing as bridges that added stability to the structure could be of different lengths, but their diameters would remain the same as previous ones.

Branches

So that the linear elements arising from particle aggregation had the same length and could be assembled with the suggested knots, a series of geometric restrictions was defined as follows:

- Each capturing particle had an "aggregation ring" corresponding to the circumference drawn by the generators of a straight cone whose vertex was the particle and whose generator angle with respect to its axis was the same as the angle of the knot B.
- When a particle moving in a given iteration reached below the collision distance (e) of the "aggregation circumference", the particle became aggregated, creating a new bar that joined the capturing particle at the point of the circumference closest to the captured particle.
- When aggregated, the bar was created as well as its twin symmetric pair with respect to the cone's axis, so that a complete bifurcation was produced from the capturing particle.
- In the case where two particles were at the necessary distance of aggregation, the one closest to the circumference would be the only one to be added.

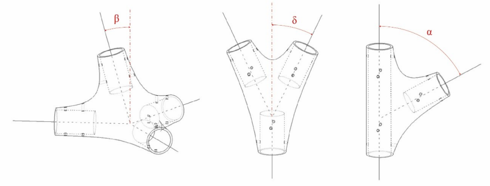

Figure 5
Proposed discrete set of transitions: knots A, B and C.

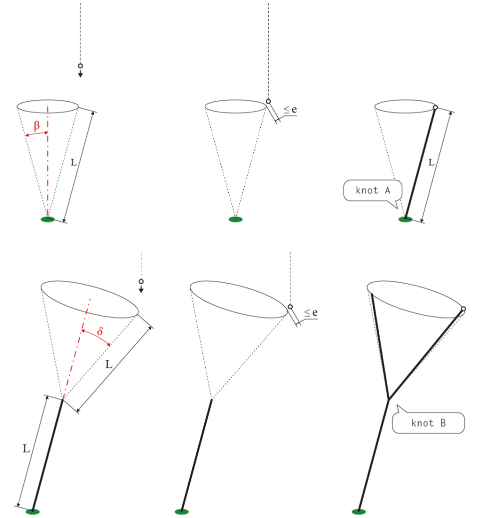

Figure 6
Generating branches: aggregation of particles in motion

- Knot A was located in the first capturing particles. The aggregation rules were the same except that the twin of the aggregated bar was not generated.

When this process is repeated over successive iterations, a branched structure gradually builds itself, in which the same restricted angles between the bars are continuously maintained (see Figure 6).

Bridges

The knot C was used to create bridges between different bars of the structure generated by the aggregation of particles, thus introducing the phenomenon of inosculation into a DLA pattern.

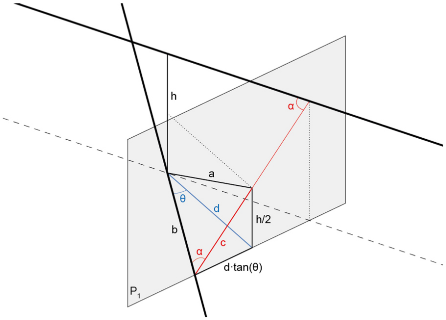

Figure 7
Segment leaning on two straight lines forming the same angle with respect to both.

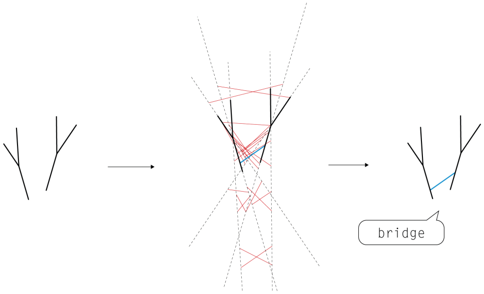

Figure 8
Example of application of the bridge creation restrictions. The bridges that did not meet the conditions were discarded (red), the others were generated (blue).

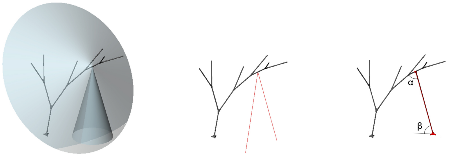

Figure 9
Aerial roots generation: intersection between the two cones and arbitrary selection of one of the resulted lines.

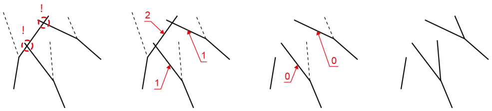

Figure 10
Example of how the auto-intersection discarding algorithm worked.

A geometric problem arose: that of finding a segment that would lean on two straight lines forming the same angle (α) with respect to both. To solve this problem, a graph was made of a typical case (see Figure 7). It was necessary to define the plane whose intersection with the straight lines produced the points enabling to draw the segment we wanted to create. The expression (1) indicates the distance between the intersection planes and the segment with the minimum distance between the straight lines. For each pair of lines, there were 2 or 4 possible solutions, depending on angle α and the angle formed by the lines between them.

$$d = \pm\sqrt{\frac{-h^2 \cdot \cos^2(a)}{4 \cdot \tan^2(\theta) \cdot (\cos^2(\theta) - \sin^2(\theta))}} \tag{1}$$

At each iteration, the routine calculated the hypothetical bridges between all the bars (see Figure 8). Of all those possible solutions, those that presented the following conditions were discarded:

- One or two ends of the bridge were supported outside the bars.
- One or two ends of the bridge were located very close to a bar knot.
- The bridge length was less than L_B min or greater than L_B max.

Aerial roots

While bridges created tree-tree or branch-branch collaboration situations, aerial roots increased tree-soil collaboration. This connection was addressed by adding type A knots where the root started from the ground and type C knots when meeting the supported branch. The routine calculated all possible aerial roots at each iteration. To do this, an intersection was built between conical surfaces with the vertex at the midpoint of each of the structure's bars. The first cone defined the geometric location of the lines that formed the angle α with these bars, while the second cone defined the geometric location of the lines that formed the angle β with the ground. The resulting intersection segments (if any) were two and were symmetrical with regard to the vertical plane containing the supported bar (see Figure 9).

As in the case of bridges, for the creation of aerial roots to be considered, the length of the roots had to be within the $[L_{AR\,\mathrm{min}}, L_{AR\,\mathrm{max}}]$ range; this restriction was necessary to avoid adding very short or very long bars. If the intersection segments passed this filter, the programmed routine arbitrarily discarded one of the two and defined the other as the aerial root to be added. In this way, a knot C appeared at the junction between the supported bar and the aerial root, as well as an A knot at the junction of the latter with the ground.

Self-collision avoidance

To ensure the viability of the structure's construction, there were some exceptional cases in which bar aggregations did not occur:

- If an aggregated branch crossed the surface of the ground, it would be discarded.
- If an aggregated aerial root, branch, or bridge intersected with another existing element, then it would be discarded. If it was a branch, it would not generate its twin pair when discarded.
- If an aggregated branch element did not intersect with an existing element but its twin pair did, then the former would be generated but the latter would not, leaving the bifurcation knot's mouth unoccupied.
- If two or more of the same type of elements aggregated in the same iteration intersected with one another, a discarding algorithm was developed that counted the incompatibilities of each bar with respect to the others, and eliminated the one that had the biggest number of incompatibilities (see Figure 10). The process was repeated until there were no bars with incompatibilities left.

MODEL TESTING

Running the virtual

A digital implementation of the method was carried out. The simulation was carried out within a three-dimensional domain of 20x20x20 meters. The collision distance was set at 0.1 meters. The length of the bars generated by aggregation was 3 meters. For bridges, a range of validity between 2 to 7 meters was established. Figure 11 shows the growth of the aggregate structure over 800 iterations.

One can observe how little material was added after 300 iterations, while in the last 200 iterations of the simulation the structure practically doubled its maximum height. This is because when one capturing particle caught another, it completed its capture capacity, but created a bracket in which two capturing particles appeared; i.e., as the structure grew, its ability to add more particles increased. At iteration 400, two of the three trees were united by several bridges, and developed some aerial roots. At iteration 600, the whole structure was highly consolidated.

Figure 12 shows the difference between branches generated by aggregation and branches added by the algorithm as a strategy of stability inspired by plants. As in inosculation events, some bridges connected the branches of the same tree and others connected the branches of different trees. These elements are expected to be effective at reducing any displacements of the structure that could be produced by external loads such as wind. The aerial roots appeared when a bar formed an angle close enough to the ground, that is, when it grew in a horizontally-oriented direction. These elements increased the supporting points and avoided pronounced bends generated by branches expanding laterally. At each iteration, all previously created elements could support a new bridge.

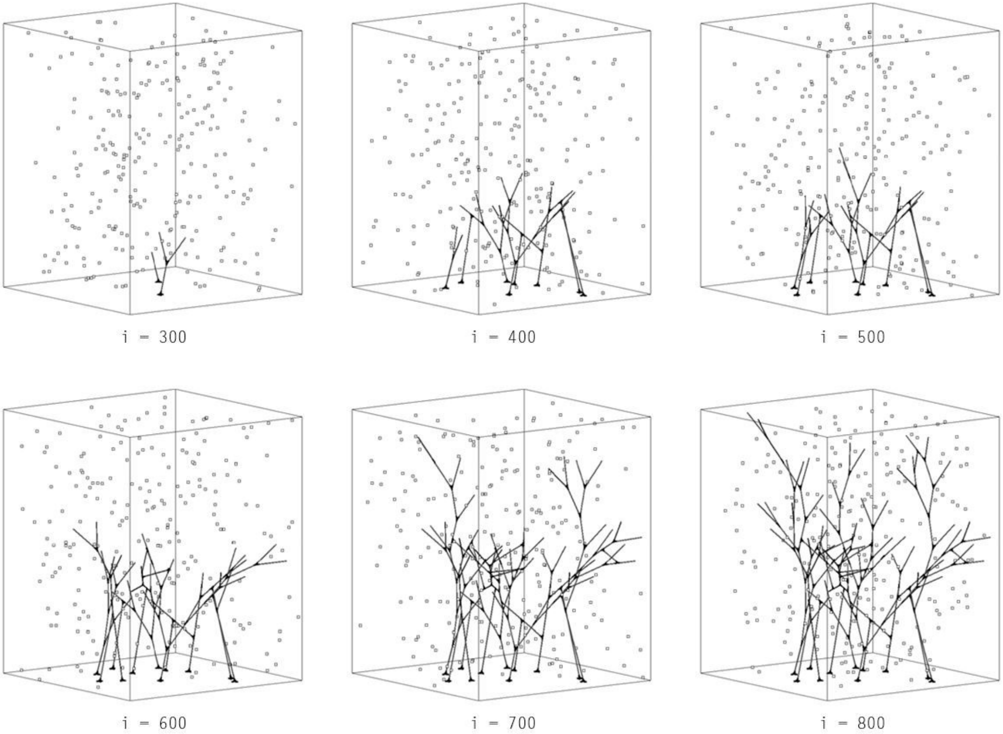

Figure 11
Growth of the structure over 800 iterations.

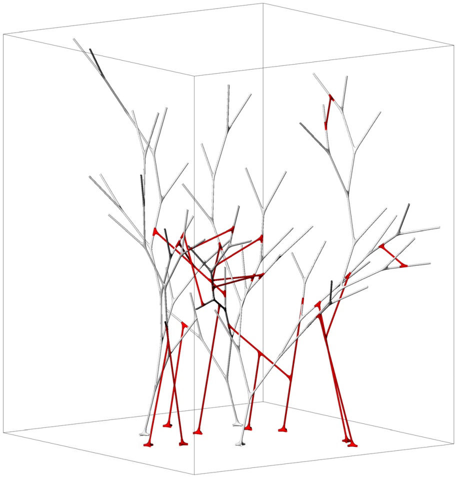

Figure 12
Structure after 800 iterations: branches (grey), bridges and aerial roots (red).

The algorithm thus allowed the creation of second order bridges, that is, bridges that rested on another existing bridge and a bar or on two existing bridges. In the same way, aerial roots could also be added to branches or bridges without distinction. This condition showed how by introducing these strategies, the topology of the DLA pattern acquired greater complexity and showed further levels of emergence.

Building the physical

The "Arbol de la lluvia" (Rain Tree) was a small installation that was built at the gardens of Medellin Faculty of Architecture (Universidad Nacional de Colombia) between 2nd and 4th of May 2018. It was predesigned at the University of Alicante and made with

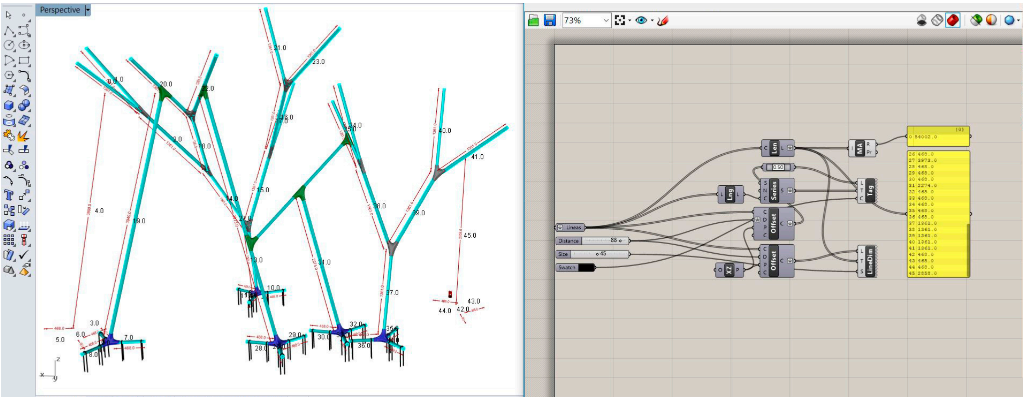

Figure 13
Parametric model of the “Árbol de la lluvia”.

Figure 14
“Árbol de la lluvia” in front of Faculty of Architecture in Medellín University. Bars (RDE 21 PVC 1.1/4”); knots (PLA 1.75mm with printing time 5-10 hours each one)

the collaboration of Medellin’s UNAL Fab-Lab. It is the exact replica of the digital model explained in 4.1. section, and specifically corresponds to iteration 500 shown in Figure 11, reaching a total height between 4 to 5m. It was thus generated by means of DLA aggregation, to which bridges or inosculated bars were added. It follows the line of the research that started with an artificial tree mounted a year before by the Universities of York (Toronto), TU-Delft and Alicante (Serrano et al. 2017). Reactive artificial plant species were added to this installation: they played the part of bird feeders and emulated exchanges between living and inert materials thanks to devices controlled by Arduino. A previous thought-provoking work had consisted in looking at what kind of native tree was located next to the installation. A previous thought-provoking work consisted in looking for the native tree to host the installation.

Finally, a monumental *Ceiba pentandra* that looked like a set of bifurcations produced by a DLA growth pattern was chosen. At the discrete design level, the skeleton was formed by only three types of knots (see Figure 13), so the difficulty lied not in the variability of the manufactured knots but in the control of the exact orientation of each part and of the whole. The supports were arranged on a horizontal plane and started with a certain angle with respect to the vertical angle, which, in fact, made the system more dynamic. Due to the time it took to execute the knots (each know took several hours of 3D printing), only three quarters of the total were printed in the end.

CONCLUSIONS

Branched structures have aroused the interest of architects and engineers due to their efficiency at transmitting loads to supports. Standardizing knots in free structures is rarely implemented because current production tools such as numerical control make it possible to manufacture structures formed by an unlimited number of different elements. Nevertheless, non-standard constructive elements manufactured specifically for a particular design are hardly useful in other configurations. This paper suggested going in the opposite direction, and follow the guidelines of combinatorial design (Sánchez 2016).

A virtual model was proposed to design free-form branched structures with a reduced number of unique elements, based on the work of Busch (2011). An algorithm was programmed and applied geometric constraints to the DLA model permitting assembly based on discrete units. As a stochastic process, the DLA was subject to a succession of random events that resulted in a different form each time. In this context, the algorithm has been shown to be effective in preventing incompatibilities, avoiding the self-intersection of the structure's bars. Extra elements were incorporated that reinforced the stability of the DLA clusters, inspired by strategies found in plants. This constitutes a novelty. The benefits of these changes in the topology of branched structures can be inferred from the work developed by Klemmt (2014).

The work presented in this paper constitutes a first approach to the application of inosculation topological strategies, and it can be understood as a fertile field of research. As future work, the capacity of cooperation between inosculated artificial trees and other structural systems can be explored. The assembly of "Árbol de la lluvia" installation has demonstrated the potential of combinatorial design, simplifying the manufacture process and the prevention of mistakes associated to multiple construction components.This experience invites us to speculate on what other typologies of elements, small enough to be 3D printed, deserve to be considered from this philosophy of combinatorial design.

And finally, what kind of architecture is approachable thanks to the performative condition of the virtual and physical model described in this paper? Probably, one in which the contingency and biomimetic predominate over the cartesian and pure formal; one that tries to learn from intelligence of collective behaviours (agents); one ready to imbricate bodies, machines, code, discourses and space.

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