Making customized tree-like structures Integrating algorithmic design with digital fabrication

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***Abstract**. The ultimate goal of this paper is to contribute for the discussion on the role of digital technologies in architecture, focusing on the convergence of generative design systems with digital fabrication processes for expanding design capabilities. It presents a generative design system of customized tree-like structures for supporting irregular roof surfaces, as an alternative to conventional architectural design processes. It discusses the introduction of an algorithmic and parametric approach to design problems as a methodology for promoting design experimentation and enabling the fabrication of complex design configurations.*

***Keywords**. Generative Design System, Parametric Design, Digital Fabrication, CAD/CAM, AutoLISP.*

Introduction

In traditional design processes, architects work with aesthetic, functional, technical, economic and social premises, which they manipulate to inform their quest for an adequate design proposal. Digitally mediated design processes may enable a similar approach, but they also may lead to the use of pre-defined systematized methodologies. This algorithmic approach to architectural design (Terzidis, 2006) builds on the computer's ability to process large amounts of data and encode complex relations among different design constraints and entities. This approach requires one to analyze, interpret, and model design phenomena, that is, both design objects and the processes to create them.

The development of such algorithms, when based on a conceptual interpretation of architectural phenomena, might contribute for advancing architectural design knowledge. However, for the manipulation of algorithms to be considered an act of designing it needs to be part of a wider framework for approaching design problems. If we succeed in doing both, the computer might become an active tool in the creative process that may lead to original and differentiated solutions to architectural problems, difficult to attain otherwise.

Part of the novelty of such solutions results from the ability to produce designs tailored to specific contexts that are composed of non-standard parts. This new paradigm is in sharp contrast with the modernistic approach which was based on the use of standard processes and parts. The new paradigm requires the convergence of algorithmic design with digital manufacturing technologies (Kolarevic, 2006). Although this paradigm has led to the generation of complex geometries and the rediscovery of curved shapes, its major contribution is on how geometric data is generated and condensed in a digital model to be directly applied to the production of customized architectural solutions using digital manufacturing. If in the old paradigm architects built what they could represent and represented what they could build (Mitchell 2001), in the new paradigm they are less limited in this regard, due to the integration of generative design systems with digital fabrication technologies.

Design problem

Departing from the assumption that digital technologies increase design possibilities, the described research presents a case-study that implements a parametric design system for generating and making irregular clusters of tree-like structures. The idea for this project departed from the observation of Gare do Oriente designed by the architect Santiago Calatrava and built in Lisbon in 1998. The building is composed of two main parts: a complex-shaped concrete grounding that supports a repetitive metal tree-like structure. Despite its futuristic outlook, the materialization of the concrete grounding required complex formwork built by skilled carpenters through a laborious handcrafted process. In contrast, the repetitive roof structure was built after an industrialized process. Volker (1997) showed how digital prototyping, namely an additive process like stereolithography, could be used to efficiently design and build formwork for concrete shapes like the grounding. The goal of the project was to enquire into the possibility of using digital techniques to design and fabricate irregular tree-like structures, in short, to avoid repetition in an industrialized process. To accomplish this, the solution was to develop a generative design system encoding the parametric geometric relations of a class of tree-like shapes and then use a digital fabrication system to materialize the output of the generative system. Both systems are briefly explained below.

Designing system

There were five fundamental issues in the development of the generative design and fabrication system. The first was the choice of the class of shapes to encode. Figure 1 (left) shows the basic selected shape, which corresponds to the archetypical idea of a tree: a trunk that branches off recursively. For the sake of simplicity, branching was kept to a minimum of two both in breadth and in depth. The second issue was the selection of a paradigm for encoding knowledge about the form. In the literature, L systems have been used for encoding tree-like shapes. L systems are particularly suitable for simulating natural growth. However, this was not a concern in the current case study and parametric design was used instead. The parametric relations of the chosen form are shown in Figure 2 (right). The third issue was the choice of implementation framework. The generative design system consists of a program written as a plug-in to AutoCAD using AutoLISP, the scripting language of Autocad. Autolisp was chosen because Autocad is a wide-spread CAD package and Autolisp is a fairly simple and flexible scripting language, which was appropriate to illustrate how designers could develop their own design systems from an existing CAD platform. The fourth issue was the selection of a material and a fabrication technique. Following the approach taken by Calatrava in the design of Gare do Oriente, in which he used flat metal sheets to construct the form of its tree-shaped structures, a cutting process was selected. The idea was to use a laser-cutter for making a wooden scale models and then a water-jet cutter for fabricating a real-scale metal prototype. Finally, the fifth issue was the selection of an assembling process. In Gare do Oriente, the flat metal parts are welded to one another. Although welding is an effective process, it depends on skilled manual labor, which can slow the production process and defeat mass production goals. As such, the system was designed to rely on the use of interlocking parts, which could be complemented by a fastening process with bolts in the prototype. This paper focuses on the fabrication of the scaled model and the changes required for making the prototype are discussed at the end.

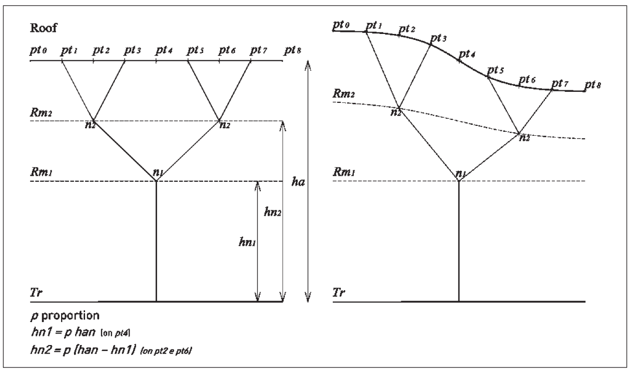

Figure 1. Parametric relations of tree-like components.

Implementing the system

The design system was implemented in a modular fashion in successive stages of increasing complexity to cope with the complexity of the program. First, it was developed a script for generating a two-dimensional model of a structural unit, by setting up parametric relations among its three levels of parts – trunk (Tr), primary branches (Rm1), and secondary branches (Rm2) - the user-specified roof and the ground. Then, the script was expanded to permit the user to specify the number (n) of structural units. Then it was further developed to generate a simplified wireframe model and subsequently extended to generate a full tridimensional model. Finally, the script was completed to decompose and unfold onto a plane the roof and the structural units in a way parts could be manufactured by a CNC cutting machine.

Using the system

The system was developed to fulfill two objectives. The first was to explore different design configurations. For accomplishing this, the design system sets parametric relations between the roof surface and each structural unit, thereby allowing the user to explore different design alternatives by playing with the following design variables: the geometry of the roof, the number of structural units, the proportion among their parts, and the thickness of the manufacture material. The second objective concerned fabrication and it is accomplished by automatically generating the information required to produce the various parts using a CNC cutting machine. To accomplish both objectives the user must go through a 4-phased process, diagrammed in Figure 2 and described below.

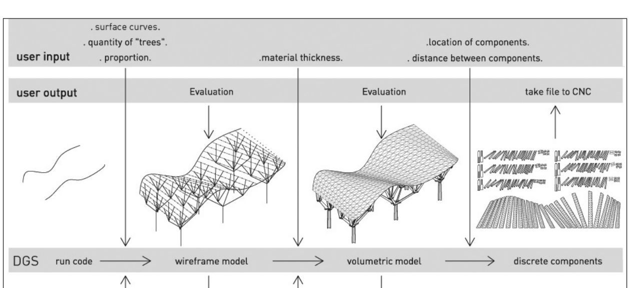

Figure 2. DGS inputs and outputs per stages.

1. Data input / mapping the surface

Before running the script the user must draw the two curves that define the roof surface. Next, the user needs to select these curves and indicate the number of structural units, in directions n and m. Then, the script connects the geometry of the surface to the geometry of the structural units, by generating a grid of points along the surface, namely, 91 points for each structural unit (8 x 8 cells in n and m), 16 of which are the connection points of the roof to the Rm2 branches.

2. Drafting / evaluation

In this stage, the system generates a simplified wireframe model to enable the user to evaluate the overall geometry of the solution. The structural units are defined through a geometric relation between their parts and the roof: the starting point of the trunk corresponds to the vertical projection of the center point of each structural unit roof grid; the endpoint of the trunk is the starting point of the 4 branches Rm1; the endpoint of these branches are the starting points of the 16 branches Rm2; and finally the endpoints of thse branches are points on the predefined roof surface grid. The z coordinates of the node points are to calculated by asking the user to define the proportion (p) of height of the trunk relatively to the height of the tree (ha), thereby obtaining the height of the node that connects the trunk to branches Rm1 (hn1). The height of each node that connect branches Rm1 to branches Rm2 (hn2) is obtained by multiplying the proportion p by the difference between the height of the tree at the node (han) and the height of the node connecting the trunk to branches Rm1 (hn1), that is, hn2 = p (han-hn1).

3. Designing the components

The design of the components is constrained by the manufacturing process, namely a CNC cutting machine, and so their shape is based on the interlocking of vertical and horizontal planes. (Figure 3)

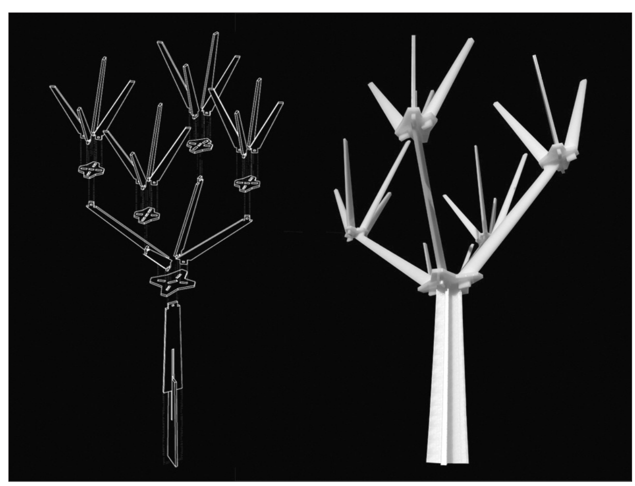

Figure 3. Tree-like structural unit: assemblage scheme and digital model.

To define the geometry of each structural part, the script retrieves data from the wireframe model, and then asks the user to specify the width of the lower end of the trunk (Trb) and the thickness of the manufacture material (e). The widths of the different parts vary to guarantee structural stability by placing lighter components on the top. The lower end of the trunk has the widest section of all the parts, and the upper end is 75% of the lower end. The same rule is applied to the branches, which also are proportionately narrower than the part immediately below.

Since the geometric complexity of the roof depends on user-prompted data, for decomposing it into parts, the script uses a process of triangulation to rationalize the surface. This process starts by retrieving the data associated with points on the previously defined roof surface grid, and then transforming this grid into a triangular mesh. More points can be defined by interpolation so that the resulting mesh becomes closer to the original curved surface.

4. Designing for manufacture

The development of the design solution is completed at this stage, and the subsequent stage is to prepare the information for manufacturing. This encompasses two steps. First, since CNC cutting machines, can only read two-dimensional digital information, the script unfolds the parts onto a plane and draws them in two dimensions. Second, it labels all parts, an essential feature for assembling the model, considering that each structural unit has 27 different parts and supports 144 different roof parts. In addition, the script distinguishes between cutting and engraving lines by placing them onto different layers. Once this stage is completed, the user can send the file to the cutting machine and then assemble the model.

Discussion and Conclusion

To test the system, it was decided to design and manufacture a physical model at the 1/50 scale, before proceeding to the fabrication of a full scale prototype. This model was formed by an irregular roof surface and six structural units (n=3, m=2) defined by the following variable values: the proportion among structural units, p=0.45; the width of lower end of the trunk, Trb=1.2 m; and finally, the thickness of the material, e=12.5 cm. As mentioned above, the technology used for manufacturing the parts was a laser cutter available at the Rapid Prototyping Laboratory of the Technical University of Lisbon School of Architecture.

The choice of material for manufacturing the 162 structural parts (27 for each tree) was determined by material thickness and stiffness - wood cardboard 2.5 mm thick (12.5 cm in real scale). It took about forty-five minutes to cut and engrave the components. For manufacturing the roof, the 768 parts that resulted from triangulation were aggregated into 24 strips of 32 triangles each. This strategy facilitated cutting and assemblage and it was possible because the material was flexible enough, but it would be difficult to follow in the production of the prototype. The photo of the resulting model is shown in Figure 4.

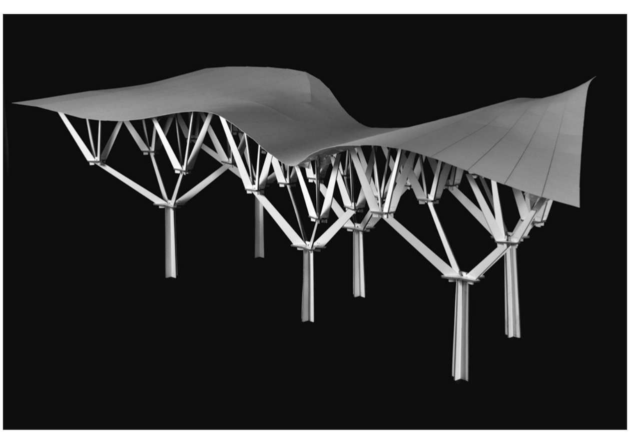

Figure 4. Photo of the physical model.

In short, the test showed that the system was a successful tool for exploring varied design configurations of tree-like structures and producing them using CNC manufacturing technologies, but that it also had some important limitations. The design, fabrication, and assemblage of the model took one and a half day, which is a quite good time for a model of such geometric complexity. However, by analyzing solutions with a wide range of surface geometries and structural proportions (Figure 5) it became clear that some solutions would not have structural liability, due to the roof surface degree of curvature, to its height, to the few number of structural units, to the proportion of the structural parts; and to the thickness of the material. Therefore, future work should include structural performance assessment to either find optimal configurations or to impose constrains on variable values.

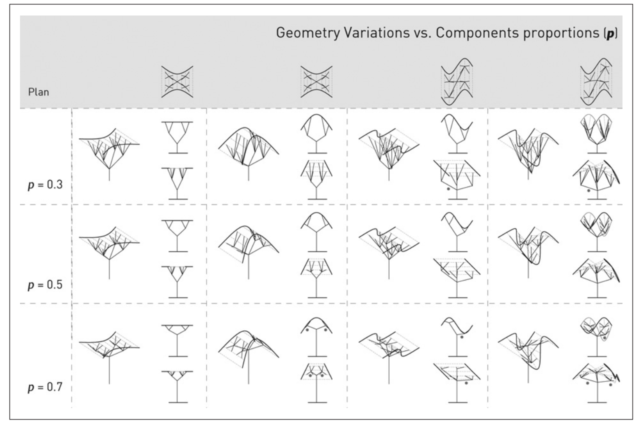

Figure 5. Geometry variations vs. components proportions.

In addition, to expand design possibilities and respond to real-world design contexts, other features should be considered as well. First, foresee the possibility of the ground to have topographic variations. This could be accomplished by following a strategy similar to the one used for the roof. Second, adapt the morphology of the structural units to the roof, by varying the number of levels and branches. And third, develop feasible connections among roof parts, and between the roof and structural units. In the current, the roof simply rests on the structural units, but customized connectors need to be added to guarantee stability under weather conditions.

A laser cutter produces insignificant waste of material while cutting, and so it is not necessary to foresee tolerances in the design of the interlocking parts because they are accurate enough. However, this is not the case of other cutting technologies, such as water-jet cutting. This means that in the design of a full scale prototype, tolerances needed to be taken into account.

The selection of CNC cutting machines as the manufacturing technology was adequate not only because it was in accordance with the strategy used by Calatrava in the design of Gare do Oriente, but also because these machines are more accessible, common, and cheaper, than other digital fabrication technologies. However, the use of CNC cutting machines constrains the selection of manufacturing material and the design of parts. The material has to be flat and stiff enough for parts to be self supporting. These machines also require one to work on the design of the connections. As components are flat, connections have a key role in enabling the complex geometry and in tying the structure together.

In summary, the proposed system achieves some of the research objectives outlined at the outset: it is effective for exploring varied design configurations of tree-like structure and in guaranteeing their efficient fabrication.

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