Symmetry, Rules and Recursion
How to design like Santiago Calatrava

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Abstract. *This paper presents a parametric shape grammar that explains the generation of the structural forms of the Spanish designer Santiago Calatrava. The shape grammar is divided into two separate grammars a lower level grammar and a higher level grammar. The lower level or first grammar is composed of rules to generate a "fundamental unit" design, which has the characteristic to be a single component with non-repetitive parts that becomes the primitive object of the design. The higher level or second grammar is composed of rules that generate the overall design by recursive application of Euclidean transformations to the fundamental unit. We concentrate our discussion on the higher level or second grammar to demonstrate the process of generating complex designs by application of simple rules.*

Keywords. *Shape Grammars, Parametric Design, Design Rules, Complex Structures.*

Introduction

Analytical Shape Grammars are mostly used to reveal underlying compositional principles of a particular design or group of designs. They embody the theories of composition of a design in a visual mode, regardless of the design process. That is a grammar may not be an accurate representation of the original design intentions of the designer, nor correspond to the designer's creative process. However, analytical shape grammars are very useful to unveil possible strategies for a particular design language or a selected corpus of work, even if it is from a single designer of a different ones language in a period of time. This paper presents one portion of an analytical shape grammar on the work of Spanish architect Santiago Calatrava.

The corpus of work is limited only to buildings and small structures (awnings, canopies and small roofs) designed and build between 1983 and 2002, therefore bridges and other works completed and/or designed after 2002 where not considered in this research. A catalog of 38 designs, including both built and unbuilt works where selected as the corpus for the grammar.

The Language of Calatrava

Santiago Calatrava has developed a unique language in which structural and artistic expressionisms are combined together to form captivating spaces with components that resemble natural forms in particular of skeletal nature. According to Calatrava himself, this is the result of a constant

inquiry on solutions of the natural world and his personal interpretation into livable spaces. Calatrava's sources of inspiration are multiples, including natural forms like trees, bones, and shells; and other from artistic expression such as paintings and sculptures that depict the nature of the structural forces balaced in bodies in equilibrium.

Even though Calatrava's designs are inspired by sources other than computational nature, his design language can be captured as a combinatorial exercise of simple yet powerful rules as means of combination of other primitive objects. This paper discusses the first of a two part shape grammar on the designs of Santiago Calatrava.

Two Shape Grammars for Calatrava's Designs

The analytical shape grammar of Calatrava is composed of two parts that are implemented independently of each other for the purpose of analysis, but must be used together for the design derivations. The first shape grammar, called lower level grammar, creates the fundamental unit (primitive design) which is characteristic of the Calatrava'. The second grammar or higher level grammar generates the overall design form (final building) by recursive application of simple Euclidean transformations to the fundamental unit.

An initial assessment of the selected designs on the catalog determined that all the designs could be divided into the two separate aforementioned grammars: the fundamental unit grammar, and the overall design grammar, thus facilitating the labor of organizing the catalog. Although this paper concentrates on the rules of the overall design grammar (second grammar), I will briefly describe what is the fundamental unit.

Lower Level Grammar:The Fundamental Unit

The fundamental unit is a unique composition which has 3 main characteristics: 1) It is a composition that can be found more than once in the design; 2) It has symmetry of 1 (identity); and 3) It is the resulting design of the derivation of the lower level grammar.

The fundamental unit is the primitive object of the second grammar, where rules are applied recursively as means of combination to generate the overall designs.

Figure 1A shows an image of the design of the PTT postal center awning with its corresponding fundamental unit (Figure 1B). Another example can be found on Figures 2A and 2B of the Lucerne station hall. The fundamental unit is an entity composed of several parts that create a non-symmetrical component that is then repeated for more than once in the construction of the whole design.

Higher Level Grammar: Rules as means of combination

Rules as means of combination are the essential constituent of the higher level grammar. The grammar is composed of the fundamental unit as an initial shape, and grammar rules that are recursively applied to the fundamental unit in order to create the overall design. The rules in the higher level grammar are restricted to Euclidean transfor-

Figure 1A. PTT Postal Center Awning

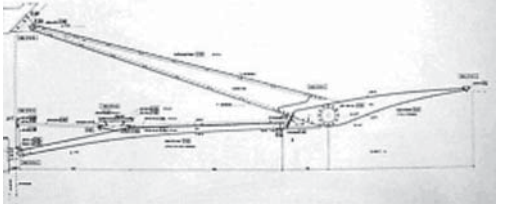


Figure 1B. Fundamental Unit of PTT Postal Center

mations: translation, rotation, scale, reflection, and any combination of them. The rule set is extracted from the catalog to generate only the existing designs.

The rules take the form of A -> B where A is the a shape and B is a shape resulting from the sum of A and the transformation of A (B=A+A(t)). In most cases only one rule is applied to the fundamental unit, resulting in a simple are repetitive design. However, there are some exceptions where two or more Euclidean transformations are applied in the same grammar to generate designs, such as the train station in Satolas airport in Lyon, France.

Recursion: Generation of Designs

The generation of the existing designs can be computed as the result of matching the fundamental unit with the corresponding rules from the rule set. The rules are applied recursively until the final design is generated.

Table 1 shows a list of selected projects from the catalog with their corresponding fundamental units, the grammar rules that are recursively applied to the fundamental rule as an initial shape and the form resulting in the overall design once the computation is completed. The designs are ordered alphabetically.

Figure 2A. Lucerne Station Hall

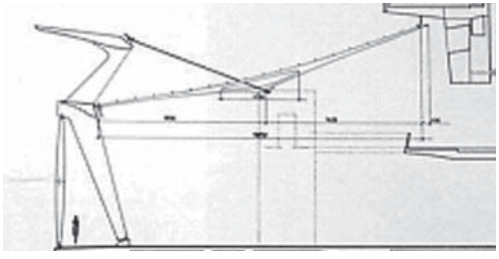


Figure 1B. Fundamental Unit of Lucerne Station Hall

New Designs

One interesting aspects depicted by the grammar is that Calatrava is continuously providing new designs for the fundamental units, or in some cases is a reinterpretation of a previously designed one. Meanwhile the higher level grammar rules are continuously repeated used in different scenarios and with different fundamental units. This shows that the most innovative aspect of the language is the generation of new fundamental units, while the invariable aspect is on the recursive application of the Euclidean transformations.

From the computational point of view, this provided an interesting machinery to generate new designs in the language since it basically a combinatorial enterprise of fundamental units designs and recursive application of simple rules to the fundamental units. In this case the new designs where generated using one the following strategies:

Other rules for existing fundamental units.
Existing rules for new fundamental units.
New rules for new fundamental units.

Other Rules

The first set of new designs was done by combining the existing fundamental units an applying the all the possible Euclidean transformation rules that Calatrava has not used. Since the number of the fundamental units in the catalog is fixed and the number of Euclidean transformations is also finite, then the possible designs are only limited to the number of recursive applications of the higher level rules. This produced finite a catalog of possible designs that Calatrava has not done but could do.

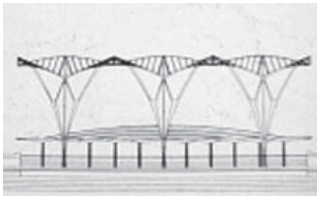
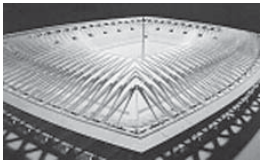
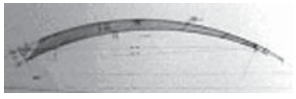
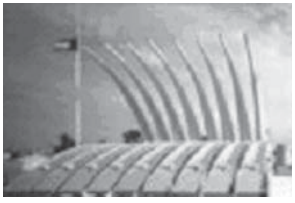
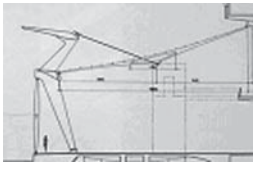
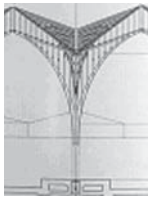
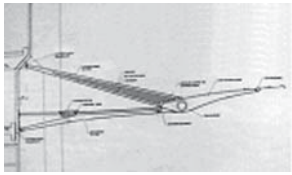
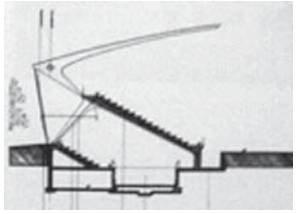
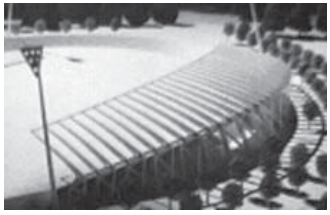
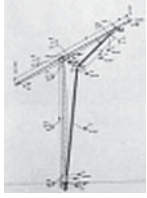
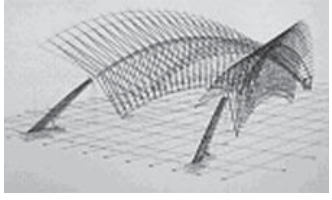
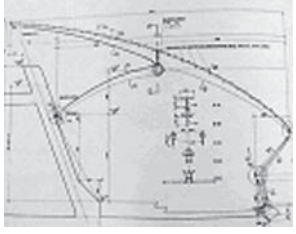
Project	Fundamental Unit	Design	Rule
Bauschaenzli Restaurant			*Translation*
BCE Place			*Translation*
Calabria Stadium			*Translation + Rotation*
Kuwait Pavilion			*Translation + Rotation*
Lucerna Station Hall			*Translation*
Orient Station			*Translation*

Table 1. Matrix of selected designs

Project	Fundamental Unit	Design	Rule
PTT Postal center			*Translation*
Salou Stadium			*Translation*
Lyon Airport Train Station			*Rotation + Scale*
Stadelhofen Station			*Translation*
Wholen School Roof			*Translation*

New Fundamental Units

The second set of designs was obtained by using new designed fundamental units from the shape rules used in the lower level grammar and applying the Euclidean transformations of the higher level grammar, but using only the ones that Calatrava has used. This provided a second catalog that is larger than the first one since any new fundamental unit can be combined with the existing transformations.

New rules and new fundamental units

This new catalog uses the combination of new designed fundamental units with the Euclidean transformations that Calatrava has not used. This mostly included combined transformations like rotation-reflections, rotation-translation, scale-glide (translation, reflection and scale), etc. In this case the catalog uses the principles established by the two grammars, where a fundamental unit is generated and a set of Euclidean transformations is applied to them to generate an overall design.

Counting the Designs

The Analytical Shape Grammar provided a catalog of finite number of possible designs that can be obtained from the existing fundamental units and the rules of the second grammar. Therefore is possible to numerically determine how many possible designs the grammar can generate

In this case the number of existing fundamental units in the first catalog is 38 and the number of possible Euclidean transformations is 4. Since all the fundamental units in the catalog where essentially different, then the total number of designs in the first catalog is obtained by multiplying 38 by 4 for a total of 152 designs, of which Calatrava has originally designed 38 leaving 114 possible new designs.

In the second catalog the possible combinations of existing fundamental units with new Euclidean transformations is larger than the first one. If we take into account the possible number of Euclidean transformations and their combinations we have a total of 24, which then combined with the 38 fundamental units in the catalog for a total of 912 new possible designs with 874 new designs not done by Calatrava.

The third and fourth catalogs use new fundamental units with existing transformations and new transformations respectively. The number of designs will depend on the number of possible new fundamental units generated by the grammar.

There are unique cases in which the fundamental unit becomes the design itself by using only one rule in the form of creating an identity A->A. Such is the case of the Barcelona tower for the Olympic Games of 1992 (Figure XX), and the Sondica airport control tower in Bilbao.

Conclusions

The use of an analytical shape grammar served for the purpose of understanding the work of Santiago Calatrava, however there might be substantial limitations when such grammars are not compared to the actual process of the designer. It is important to acknowledge this limitation of a shape grammar for analysis where the important aspect is to explicitly convey what the design is, instead of the reasons of why something is design in a certain way.

The general strategy of subdividing the grammar into two levels proved to be of benefit to understand the design language. In several occasions when the grammar was explained to students they responded with a better understanding of the design language of Calatrava. The levels also served to differentiate the unique components versus the ones that are repeated throughout the whole design.

The lower level rules are more complex nature and deserve the complete attention which is beyond the scope of the present paper and subject to future research.

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