GEOMETRIC TRANSFORMATION AS AN ARCHITECTURAL FORM GENERATION STRATEGY: A CASE STUDY IN THE WORK OF SANTIAGO CALATRAVA

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Abstract: The present undergoing research aims at studying the geometric transformations and parametric variation of shapes that are present in the work of Spanish architect Santiago Calatrava. The first phase of this research consisted of a literature review about the different types of shape transformations, from Eucledian to non-linear; concepts in architectural composition; the work of Santiago Calatrava and his use of natural analogies. Two building designs by the architect were selected and represented in an abstract way that reinforces the transformation aspects of the compositions. In the next step of the research physical models of each design will be produced, with the use of digital fabrication techniques. As a result, we expect to be able to visually explain the concept of geometric transformation as a strategy to generate architectural form.

Keywords: geometric transformation, parametric variation, generation of architectural form, Santiago Calatrava.

1. INTRODUCTION

The present research aims at studying the geometric transformations and parametric variation of shapes that are present in the work of Spanish architect Santiago Calatrava. The work is still in progress, and will be finished by June 2007.

The study is being carried out by an architecture student, advised by an architectural design professor, as part of an initiative to encourage scientific investigation among undergraduate students at the State University of Campinas. To develop this study, the student received a one-year grant from CNPq, the Brazilian National Research Council.

The first phase of the research consisted of a literature review about four topics: the different types of shape transformations, from Eucledian to non-linear; concepts in architectural composition; the work of Santiago Calatrava; and the use of natural analogies in architecture and in Calatrava's work. In the second part of the research, the student selected two building designs by Calatrava that he considered particularly representative of the use of shapes generated by geometric transformations. He collected information about these two buildings, which were drafted and 3D-modeled in CAD software.

In the next step of the research physical models of the two buildings will be produced, with the use of digital fabrication techniques. As a result, we expect to be able to visually explain the concept of geometric transformation as a strategy to generate architectural form.

2. SHAPE TRANSFORMATION

A study about the different types of shape transformations was conducted, looking not only at the most studied Euclidean transformations, but also at other types. The different types of transformations were organized in Table 1, according to the properties that are preserved and to the field in which they are studied, such as afine geometry and topology. A similar study is presented by Mitchell (1990), who proposes a "taxonomy of transformations".

<table>
<tr><th colspan="7" rowspan="2">Type of transformation
(Field of mathematics that studies this type of transformation)</th><th rowspan="2">Transformations</th><th colspan="11">Properties that are preserved</th></tr>
<tr><th>Position</th><th>Dimension</th><th>Shape</th><th>Orientation</th><th>Handedness</th><th>Parallelism</th><th>Proportion</th><th>Cross ratio</th><th>Conection</th><th>Convexity</th><th>Interior/Exterior relation</th></tr>
<tr><td rowspan="10">General transfor-mations</td><td rowspan="9">Non-linear (Topology)</td><td rowspan="8">Linear (Projective Geometry)</td><td rowspan="7">Affine (Affine Geometry)</td><td rowspan="5">Similarity (Similarity Geometry)</td><td rowspan="4">Isometric (Geometry)</td><td rowspan="3">Proper isometric (Euclidean)</td><td>Identity</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td></tr>
<tr><td>Translation</td><td></td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td></tr>
<tr><td>Rotation</td><td></td><td>■</td><td>■</td><td></td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td></tr>
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<tr><td colspan="2"></td><td>Scale</td><td></td><td></td><td>■</td><td>■</td><td></td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td></tr>
<tr><td colspan="3" rowspan="2"></td><td>Stretching</td><td></td><td></td><td></td><td>■</td><td>■</td><td>■</td><td></td><td>■</td><td>■</td><td>■</td><td>■</td></tr>
<tr><td>Paralel projection</td><td></td><td></td><td></td><td></td><td>■</td><td>■</td><td></td><td>■</td><td>■</td><td>■</td><td>■</td></tr>
<tr><td colspan="4"></td><td>Perspective proj.</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>■</td><td>■</td><td>■</td><td>■</td></tr>
<tr><td colspan="5"></td><td>Non-linear contin.</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>■</td><td>■</td><td>■</td></tr>
<tr><td colspan="6"></td><td>Others</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Table 1: Shape transformations, according to preserved properties.

Architectural education has traditionally given more attention to Eucledian and projective geometries, which are used in the generation of orthogonal construction documents and perspective illustrations of buildings. Recently, however, there has been a growing interest in other types of geometry, especially in topology (DiCristina, 2001).

Topology is the study of transformations such a stretching and bending, which can change an object without breaking it apart or destroying its edges. Topological transformations can always be reversed. For this reason, topology is also known as "rubber sheet" geometry.

Although questions of basic education are beyond the scope of the present paper, it is interesting to notice how, as early as in the 60's, Hungarian mathematician Zoltan Dienes (1975) proposed the introduction of topology in pre-school education, even before the introduction of Euclidian geometry. One can wonder what kind of architecture we would see nowadays if this kind of pedagogical approach had been adopted by our schools.

3. ARCHITECTURAL COMPOSITION

Architects typically apply universal concepts such as rhythm, proportion and symmetry to develop balanced, interesting compositions (Ching, 1979). These three concepts have similar meanings and origins. For the ancient Greeks, rhythm was associated to movement and regular repetition. Sculptors first developed the concept of proportion, as the relationship between the parts and the whole within a statue. Symmetry was defined in Vitruvius's Ten Books on Architecture, the very first architectural treatise, as the correct relationship between the parts and the whole of a building.

According to Ching (1979), other ordering principles in architectural composition, such as repetition and transformation of shapes, are also related to symmetry, rhythm and proportion. In modern mathematics symmetry is defined as the result of the application of isometric transformations, such as translations, rotations and reflections. Isometric transformations keep the size and proportion of the objects, while changing their position, rotation and handedness.

It is also possible, however, to generate interesting compositions by applying transformations that change an object's size and proportion. Let us consider, for example, the two buildings designed by architect Oscar Niemeyer in Figure 1. Both buildings display the typical modern movement scheme of a glass box inside a protective concrete envelope. In the left side picture, rhythm is achieved with the repetition of identical arches. In the right side building, however, rhythm results from a series of different arches. It is possible to notice that all the arches have the same impost and overall height - just the width has received different, random values.

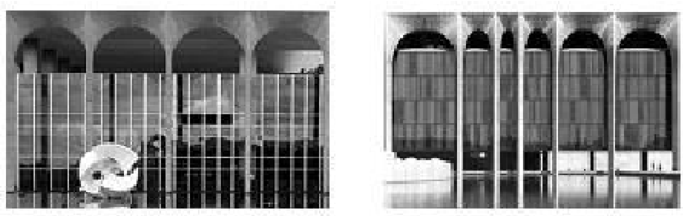

Figure 1: Two similar designs by architect Oscar Niememyer: the Brazilian International Relations Ministry building in Brasilia and the Mondadori Editore building, in Milan.

Another way of using non-isometric transformations in design is by applying a regularly increasing - or decreasing - scale factor to one or more dimensions of an initial shape. The Big Wild Goose Pagoda, in northwestern China (Figure 2), for example, illustrates this concept. Each storey has increasingly smaller width and length, while the height remains constant. Besides the scale transformation, there is also a translation in the vertical axis.

Figure 2: Big Wild Goose Pagoda, China.

The use of non-isometric transformations, such as equal or non-equal scaling, combined with other types of transformations, such as rotations and translations, enlarges the universe of possible compositional variations with a single initial shape.

According to Mitchell (1990), parametric variations of shapes can be "destructive" or "preservative". In the first case, unequal parameters are used to distort a shape, sometimes resulting in a form that does not even resemble the original one. In the second case, equal parameters are used and the new shape displays the same proportions of the original one.

4. SANTIAGO CALATRAVA

Some of the most interesting examples of the use of geometric transformation and parametric variation as an ordering principle in contemporary architecture can be found in the work of Santiago Calatrava. This Spanish architect, who has a background in art and sculpture, developed his graduate studies in structure engineering at the ETH Zurich. Among his many works are the Lyon Airport station, the City of Sciences in Valencia, the Orient Station in Lisbon and the Olympic Complex in Athens.

Calatrava believes that the study of geometric transformations is key to understanding architecture (Von Moos, 1998). This concept is present in his sculptures, which are based on transformations of cubes and other basic forms, and from which many of his buildings are derived. Figures 3 to 5 show three examples of residential towers based on geometric transformations. Figure 3 shows a building design based on translations on the horizontal and vertical directions. The building on Figure 4 is based on both translations in the vertical direction and rotations around the vertical axis. Figure 5 shows two similar designs, which display translations, rotations and progressive scale transformations.

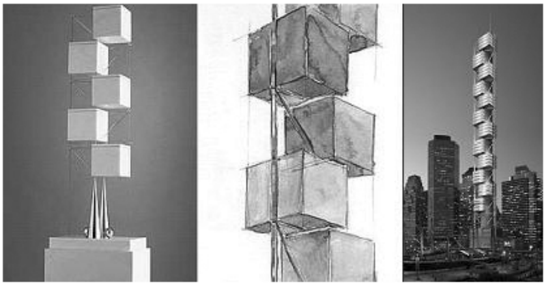

Figure 3: Left: "Torso", sculpture by Calatrava. Right: Calatrava's proposal for a residential tower based on "Torso".

Figure 4: Left: "Turning Torso", sculpture by Calatrava.Right: Calatrava's design for another residential tower, based on "Turning Torso".

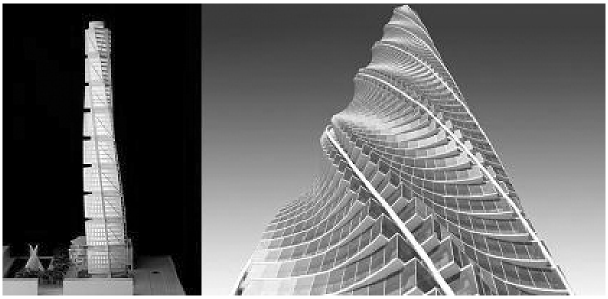

Figure 5: Other building designs proposed by Calatrava, based on translations, rotations and scale transformations.

5. NATURAL ANALOGIES

The work of Santiago Calatrava has been called bio-morphic by some authors, such as Von Moos (1998). In fact, his sketches show a deliberate interest in human and animal forms, from which his sculptures - and eventually his buildings - are derived (Figure 6.).

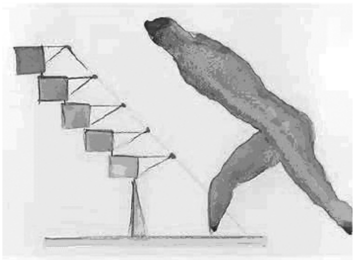

Figure 6: Drawing by Santiago Calatrava showing a bending torso and a scheme for a corresponding sculpture.

In The Evolution of Designs, Steadman (1979) asserts that nature has always been a source of inspiration for artists and architects. Typically, this influence has been present in three ways: through the use of proportions found in natural things, such as the human body; through the use of shapes directly inspired by natural forms, such as plants and animals; and through functional analogies, where the whole animal or plant, or parts of it are used as a source of inspiration. The first case can be illustrated by the use of human proportions in the work of architects like Vitruvius, Palladio and even LeCorbusier. The second case has been present mainly in decorative details, from Corinthian capitals to Art Nouveau subway entrances. The use of natural analogies by Calatrava falls in the third category proposed by Steadman, which requires greater abstraction.

Figure 7: Sketches and a table designed by Calatrava, showing antropomorfic form and function.

Calatrava's sculpture in Figure 6 not only recalls an inclined human body, but also the structure of a vertebral column, with its rigid vertebrae connected by flexible wires to a tensioned spinal chord. Figure 7 shows a more literal example of the use of a functional analogy in a table design by Calatrava: we can practically see a human body holding the tabletop's weight.

Tischhauser (1998) points out that Calatrava's work shows also great enthusiasm with the capacity that natural organisms have to change, grow, move and adapt. These characteristics are present, for example, in his kinetic sculptures, and in some of his buildings, which recall movement. Figure 8 shows a building designed by Calatrava inspired by moving wings. In this case, the feeling of movement is achieved by the use of translation, rotation and progressive scale transformations of a basic structural motif.

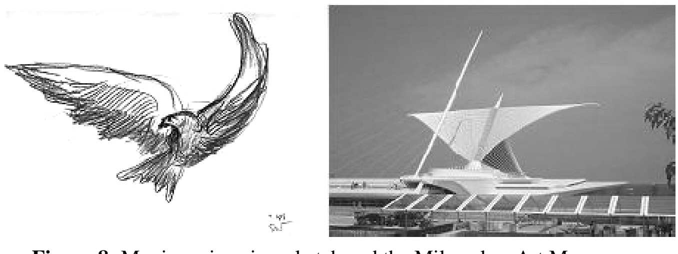

Figure 8: Moving wings in a sketch and the Milwaukee Art Museum.

6. EXPERIMENT

In the second part of this research practical experiments will be carried out. Two building designs by Calatrava that have been considered particularly representative of the use of geometric transformations were selected: a community center in Alcoy, Spain, and a train station in Lyon, France. Their structural schemes have been studied and the parts that are parametrically repeated have been redrawn and 3D-modeled in an abstract way, with the objective of making the transformations more easily understandable.

The first building, a community center in Alcoy, Spain, is an underground space located under a square. Its structure is based on a sequence of arched porticoes translated along a straight line. The sequence starts with two identical arches side by side that gradually merge into a single arch. In other words, the internal base of the arches is gradually raised until it becomes the central point of a double-width arch. In order to study and explain the parametric concept in this building, a model will be produced with laser-etched 10mm thick acrylic sheets. Each section of the structure will be etched on a separate sheet. A metal rod will be used to keep the sheets together, as shown in

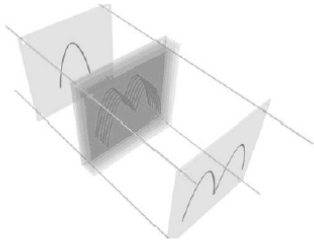

Figure 9: Computer rendering of conceptual model of Alcoy Municipal Center that will be produced with a laser cutter.

The structure of Lyon Airport station's central hall displays a series of triangular modules that are gradually rotated and scaled unequally. This central "spine" of the building will be 3d-modeled as an abstract form, and 3d-printed as separate pieces that can be snapped into each other to explain the parametric variation of the initial shape, as shown in Figure 10.

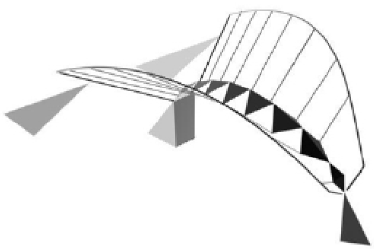

Figure 10: Computer rendering of conceptual model of Lyon Airport station that will be produced in a 3d-printer.

7. DISCUSSION AND FUTURE WORK

The aim of this undergoing research is to visually explain the concept of parametric variation of shapes that is present in two buildings designed by Santiago Calatrava. We expect that the models that will be produced as part of this research will be useful for explaining the use of geometric transformation as an architectural form-generation strategy in a clear, three-dimensional way. In the future, we expect to use these models and other similar ones in architectural design classes, in the same way that infographics have been used to explain concepts in two dimensions.

8. ACKNOWLEDGEMENTS

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