Robotic Form-Finding and Construction Based on the Architectural Projection Logic

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Abstract. In this article we analyze the relationship between the architectural drawings and form-finding, indicate that architects should reuse and redefine the traditional architectural drawings as a form-finding tool. Explain the projection systems and analyze how these systems affected the architectural design. Use robotic arm to do the experiment and establish a cylindrical projection form-finding system.

1. Introduction
According to the working mechanism of architecture, the operations of architectural design are always based on a series of geometric operations; these operations are usually functioning inside the abstract space of architecture and described by a series of drawings, such as plans, sections, elevations, perspectives and so on. In the context of contemporary architecture, design methods can be characterized by two types, the first one is translating the drawings from 2D medium into 3D objects according to the traditional projection method; the other one is purely 3D operation in digital environment. It is an undeniable fact that the introduction of computational technology has brought a huge design freedom for the latter, and the architects are able to work in a 3D atmosphere to create complex spatial forms; however, with the isolation of 2D drawings and 3D forms during the design process, the architectural drawings are just as additions of the design, representing the design result by traditional projection methods. The form-finding ability of the architectural drawings is being gradually neglected. [1]

2. Architectural Drawings and Form-finding
"Form-Finding" has a long history in architecture. As early as before the "Computer Age", the Spanish architect Antoni Gaudí had used upside down force model to explore the geometrical forms of catenary arches, such forms had been used in his projects such as Basilica and Expiatory Church and the Holy Family and Church of Colònia Güell (Fig. 1). Through using this completely new method – which is based on motion dynamics and gravity, Gaudí invented his own architecture languages and achieved his greatest architectural goal - to perfect and go beyond Gothic style. [2] The term “form-finding” was brought by the German architect Frei Otto for the first time; due to his contribution of using the physical models as design engine and form-finding tool, Otto is recognized as pioneer of the parametric design in architecture. [3] Otto was specialized in lightweight tensile and membrane structures, the forms were derived from a series of soap bubble experiments which used the surface tension of the liquid to find the minimum surface to cover a closed shape (Fig. 2). [4]
From the “nonlinear system theory” to the “parametric design”, the computational technology has brought a completely new medium to the architectural design, and it’s even altering the fundamental theories and thinking processes behind it. With the popularization of digital software, the mechanics of how architects work have changed; less and less are using traditional architectural drawings as a form-finding tool. However, the traditional architectural drawings’ ability of form-finding has played an important role in the development of the architecture with the following three aspects:

First, human beings live in 3-D world; human brain has a better ability of awareness and controllability for lower dimensions (1-D & 2-D). Through using traditional architectural drawings, such as plans, elevations, and sections and so on, architects are able to operate 2-D geometries on paper to obtain 3-D architectural forms. It simplifies the process of design and improves the creativity greatly.

Second, the design process will be stretched when use drawings as design medium, thoughts and ideas of the architects can be delivered to paper directly. During the design, 2-D drawings are much easier to perceive and operate, thus making a better condition for architects to compare and adjust, providing an intuitive means of visualized information to make decisions.

Third, the biggest contribution of the drawings is introducing the projection methods to the architecture, so that the work of architects is based on information transmission between dimensions rather than operating 3-D objects directly. Since the Renaissance, architects were no longer involved in the construction directly, but rather using the drawings to connect design and construction. [5] So that the projection methods began to affect the architecture forms. [6] The transmission between dimensions will inevitably be accompanied with adding or cutting information in some specific dimension, which makes the design results some kind of unpredictable.

There seems to be a paradox, as mentioned before, since the traditional architectural drawings can't meet the contemporary demands of creating complex forms in 3-D atmosphere due to the restriction of dimension, and also medium function of drawings to connect design and construction is being gradually replaced by computer, then how can we redefine and reuse the traditional architectural drawings as form-finding tools in contemporary architectural works? In order to answer this problem, we need to analyze the evolution of projections and drawings in the history of architecture.

3. Redefinition of the Architectural Drawings Based on the Architectural Projection Logic
The functions of plans, sections and elevations, as three of the most important architectural drawings, are representing 3-D buildings with 2-D drawings based on parallel projection methods. Parallel projections are functioning with projection lines which are parallel both in reality and in projection planes, and the work can be described as a series of parallel lines projecting the building’s geometry on drawing planes. [7] For different types of drawings, the projection lines are pointing to different
directions, if the projection lines are orthogonal relations, it will carry out the orthogonal architectural work planes - plans, sections and elevations. Under such circumstance, the architecture can be viewed as in a cube full of parallel projection lines, the architectural drawings are presented on the surfaces of the cube, and thus this cube could be viewed as the workspace of architecture (Fig. 3). On one hand, the representations of the architecture are based on the drawings within this workspace; on the other hand, as an important design medium, the drawings can also affect design through the workspace. For example, if architect use plans as design medium, the work will tend to present richness and ductility in horizontal direction; if architect use sections as design medium, the work will tend to be more recognizable on the vertical dimension. All of these reflect that the forms are affected by the types of drawings and projection methods.

Painting and architecture are both based on projection systems and then presenting the results on papers. Looking back, the shift of projection methods affected the way of expression and had revolutionary impacts on innovations of painting and architecture. [8] For example, both abandoned perspective projection method which had been used for hundreds of years in painting, Futurism adopted a dynamic projection method and tried to add time as the fourth dimension on 2-D images; while Cubism tried to overlap multiple projection systems with different vanishing points together rather than use the traditional perspective with single vanishing point to describe 3-D objects. Similarly, in architecture, architects found it’s difficult to describe and create nonorthogonal complicated forms through the traditional workspace with parallel projection system, such as the shapes of the different stones in dome, and then the stereotomy - a more effective graphic description of nonorthogonal form – was invented. Stereotomy abandoned the traditional cube workspace, combining the parallel projection with perspective projection to achieve higher degrees of freedom to operate nonorthogonal forms (Fig. 4).

In the context of contemporary architecture, architects tend to only care about the change of graphical languages, while ignoring the innovation power of drawings and projections as source of form-finding since it is difficult to create complex forms in the traditional architecture workspace which is based on the X - Y - Z orthogonal parallel projection system. On one hand, it is much easier for the architects to operate complex shapes with the help of computers, so the architectural drawings are gradually independent from the design process and only be regarded as additions to represent certain degrees of the results; on the other hand, the direct operation of 3-D shapes in digital is missing the unpredictability of forms due to the lack of conversions between dimensions. [9]
From perspective drawings in the Renaissance to the computer graphics of today, the working mechanism of the drawings as the design medium has shifted from the 2-D orthogonal projection to a multidimensional composite. The meaning of the word "drawings" becomes rich, more pointing to the diagrams with both logicality and fuzziness. Just as Neil Lynch said: "Computer Age is not giving a new style, but a new design technique. We apply computer technology in evolutionary and emerging systems, establishing an implementation and testing system make the diagrams to reality, reality to diagrams. In this new field, form is not important at all. We should explore the potential of "algorithm technology", and focus more on intelligent and logical processes from design to construction, logic is the new form." [10] So we can see that the combination of the architectural drawings with computer technology based on the architectural projection logic is the redefinition of the drawings as design medium. At the same time, with the development of CAD (Computer Aided Design) and CAM (Computer Aided Manufacturing), the contemporary architectural form-finding is not only the from top to bottom style – which is providing inspirations and references to architects during the one-way design process, but also the from bottom to top style, that set up the basis for material control and construction.[11] So, if we change the projection modes of the traditional architecture workspace, in which design is forming and operating, we will be able to explore multiple possibilities of drawings. Meanwhile, we introduce the robotic arm to connect materialization and projection, in the end, through combining the two methods’ advantages, a new design medium, with both form-finding ability of drawings and the controllability for nonorthogonal geometries, will be set up.

4. Robotic Form-finding Based on the Architectural Projection Logic
In this study, we use the KUKA six axis articulated robotic arm as the bridge to connect drawings with construction, thus establishing a medium between design and materiality, which is totally different from the working mechanism of today’s architectural design. The robotic arm is widely applied in areas of aerospace and automobile manufacturing, and it is gradually replacing the manpower by achieving precise positioning and point-to-point operations in 3-D space. The movement of the robotic arm follows the computer program instructions according to the principle of inverse kinematics, which is reaching the desired position through rotating the joints with certain parameters. [12] In recent years, with the popularity of utilizing the CAM, there are more and more robotic applications in architecture. In 2008 the Venice Biennale of Architecture, the ETH Zurich professor Fabio Mario and Matthias Koehler explored robotic construction by using bricks - one of the most traditional materials. They used six axis robotic arm to lay bricks and built a parametric curved wall, yield unusually brilliant result. ICD and ITKE of the University of Stuttgart were inspired by the inner structures of sand dollar and sea urchin, they applied seven axis robotic arm for precast productions, developed a new method of wood shell construction and finished the Research Pavilion 2011 (Fig. 5). [13]
In our research, the robotic arm is equipped with a hot-wire cutter to cut an EPS foam cube (Fig. 1), the mechanism is controlling the path of hot-wire to get a desired shape. In geometry the smooth surface we got is a ruled surface, as the parametric representation of a curved surface is

$$r (u, v) = a (u) + v * l (u)$$

In ruled surface, $l (u)$ is unit-length vector, the $v$ curve is a straight line, and ruled surface is swept by this moving straight line which is referred as the generatrix. Ruled surface had been used in architecture for long due to the clear construction logic and diverse forms. Gaudi applied isometric mapping operation method to build ruled surface like hyperboloid and parabolic, which were widespread used in his projects. [14].

In traditional, the construction of ruled surface is the bottom to top style, which starts with material and ends with construction, the process is dominated by the materiality logic. While, the contemporary construction is usually the top to bottom style based on the computational technology, the process is dominated by form. So we imagine operating the robotic arm with the architectural projection logic so that we can break the unidirectional transmission between digital and physical, set up a form-finding method with the construction of the ruled surface.

At the beginning, we simulate the movement of the robotic arm by using Grasshopper plug-in of Rhino (Fig. 7), the simulation shows that:

1. The trajectory of hot-wire make a ruled surface, hot-wire is the generatrix of the surface.
2. The movement of the two endpoints of the hot-wire line generate two separate space curves.
3. The ruled surface can be described as a straight line sweeping through the two space curves.

Therefore, it’s obvious to see that how to manipulate the two space curves is the key to cut the ruled surface. Though we can modeling the two space curves in digital precisely, however, the curves cannot be intuitively controlled since the mechanism of the digital software is using projection methods to simulate a 3-D workspace and then project shapes on screen, it will inevitably increase the difficulty of control.

![Figure 7. Simulation of the movement in Rhino](image1)

![Figure 8. The two space curves can be presented and projected onto the side surface of a column around the foam cube.](image2)

In order to solve this problem, we need to reduce the dimension and create a corresponding workspace. It is apparently that the two space curves can always be presented and projected onto the side surface of a column around the foam cube (Fig. 8), so we introduce cylindrical projection to our system. The cylindrical projection is one kind of map projections and it is widely used in mapping systems around the world which is known as Mercator projection. In a cylindrical projection map, the mapping of meridians to vertical lines can be visualized by imagining a cylinder whose axis coincides with the
Earth's axis of rotation. This cylinder is wrapped around the Earth, projected onto, and then unrolled. In our system, the two space curves can be presented on the unrolled cylindrical screen first (Fig. 9), and then position in 3-D space by wrapping the screen into cylinder. It is a reversed operation of cylindrical projection and the unrolled screen is within the Cartesian coordinate system and also it could be described as the new workspace with the ability of form-finding.

![Figure 9. The unrolled cylindrical screen.](image)

In this Cartesian coordinate system, hot-wire moves along with the y axis from the top edge to the bottom x axis. So we set two curves along the movement direction, which are rail a, and rail b; then we wrapped the screen into a cylinder, so that the two curves rail a, and rail b will be positioned in 3-D (Fig. 10). By using this workspace with the cylindrical projection method, it is able to describe any kind of movement of hot-wire under such circumstance.

![Figure 10. Position rail a, and rail b in 3D.](image)

As we control the trajectory of the robotic arm with the cylinder projection method, which is a 2-D workspace, so we didn't make any predictions about the forms of the ruled surfaces. The working process is based on the architectural projection logic, multiple possibilities and unpredictable forms
are generated. During the construction, we control and simulate the movement of the robotic arm in
digital first, so that we can correct the operations in time and represent the machining process
intuitively, paperless construction will be realized. Finally, we evaluate the system by cutting the
foams and feedback the evaluation results to the digital, so that we are able to establish a circuit fusion
of digital and physical and cut the foam with logic of architectural projection (Fig. 11).

5. Conclusion

Drawings and projections are the most basic media in architectural design, it will provide a new
workspace and new way of form-finding by redefining them in digital. Explore form-finding
possibilities through changing the architectural representing mechanism of projections rather than
operating the forms directly, such as using cylindrical projection and spherical projection instead of
the traditional orthogonal parallel projection, so under such circumstances, the drawings are both
form-finding media and representation methods. Besides, control the robotic arm and by applying
different projection logics, we will eventually achieve the reconstruction of form-finding from
drawings to constructions.

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