The Preliminary Process of Synthetic Digital Fabrication

In terms of sheet metal facade

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Abstract. With the development and maturity of various digital media, architectural design process has gained considerable more freedom as compared with modernism. Digitalized virtual environment and advanced industrial machines are continuously been discussed and applied to experimental projects, creating astonishing architectural shapes which have been difficult to create in the past. Under such digital architectural trend, this research analyzed various digital fabrication methods through different architectural projects. By comparing the properties and processes of each fabrication manner, we aim to come up with a preliminary framework of an executable fabrication process which synthesized advantages from multiple fabrication methods.

Keywords. Digital fabrication; Industrial robot; Sheet metal; CAD / CAM.

INTRODUCTION

With the help of various computer-aided design (CAD) and computer-aided manufacturing (CAM) techniques, designers finally have the ability to precisely and directly construct architectural components in a real world scale. The advanced techniques applied significant effect on design and production processes, and dramatically changed the possibility of architectural form. Compare with modernism, in the digital age, relationship between design and manufacture is even closer and keeps challenging the design-to-production chain we knew. The phenomenon of evolving digitalized design processes has become a new territory that architects highly interested in and keen to explore the possibilities (Kolarevic, 2003). This increasing passion brought a variety of digital fabrication methods in accordance with the properties of material and design demands.

In order to find the optimized solution, digital design process has to consider both virtual and reality conditions. As a result, the distinction between digital environment and physical world has gradually got blur.

Therefore, in the architectural context that stressed on virtual and reality cooperation, how to take appropriate digital fabrication method for realizing architecture components becomes a significant issue. Because it is not only influenced architecture performance, but also altered construction cost and spending time. According to the property of different computer numerically controlled (CNC) machines, we could classify digital fabrication methods into four different types, such as two-dimensional cutting, subtractive, additive and formative fabrications.
Two-dimensional cutting is the most commonly fabrication technique which handles sheet material by various two-axis motion machines. The production strategies of this method usually include contouring, sequential section and triangulation. By composing numerous planar components, designers could define different architectural tectonics. For instance, Dynaform pavilion (Figure 1) took 2D fabrication as main manufacturing method (Afify and Elghaffar, 2007). By the help of laser-beam, designer could freely define the contour of structure on a steel plate and cut sixteen customized frames to support the entire free-form shell.

Subtractive fabrication is a method that removes extra volume from a solid material and leaves the expectation result of designer. In the past, the concept of this technique had been widely applied in various art forms, such as carving, etching and engraving. Those techniques highly relied on the proficiency of craftsman, and limited by production time and human power. Now days, with the assistance of multi-axis milling machines, this artistry skill could transform into a system which is instructed by a set of code and precisely manufactured under digitalized power. For example, the perforated wall project (Figure 2) applied six-axes industrial robot
with a spindle for milling styrofoam boards. It took the character of subtractive fabrication, accurately cut out tilted holes with specific angles which were defined in custom script. Each hole directly reflected the shape in the visual environment. It substantially improved the skill of subtraction concept.

Additive fabrication is a converse method from substraction, the concept of it is to add material in a layer-by-layer fashion. For hundreds of years, construction and materialization logic of architecture mainly builds on this concept. For example, people build up a wall through stacking numerous bricks. It is a classic process to layer small units together. Then, effect by the tendency of digital manufacture, additive fabrication also has dramatically changed. Various digital devices had been invented and brought different digital additive methods, such as layered manufacturing, solid freeform fabrication or rapid prototyping. All the manners gave designers great freedom in exploring potential of architecture form. However, additive fabrication still has its limitations. For instance, it is normally limited by the size of objects that it could produce, costly equipment and long production time. As a result, models that made by this method would rather small and trend to conceptual making. According to this situation, some researchers began to study experimental techniques for making large-scale components. For example, the programmed wall project (Figure 3) took six-axes industrial robot to do highly repetitive tasks and achieved the layer-by-layer result. By the logic of control program, robot arm could repeatedly position bricks in the correct locations. The resolution of this project depended on the size of deposited material which is a brick. It promoted the scale of additive fabrication into a large-scale level.

Formative fabrication is a method refers to apply force on material. Through different type of strength, such as heat, steam, and mechanical force, this method deformed material into an expectation shape that designers wanted. For instance, in the car industry, they took digitalized device to apply various stressing and bending forces on steel panels. While the applied force past the elastic limit of sheet metal, it would permanently deformed into stable streamline shape. This deforming process is highly relied on the cooperation between the physical...
property of material and the category of given force. In the Robofold façade project (Figure 4), it took industrial robot as manufacturing media. Through giving appropriate force from specific angles, sheet metal folded into a three-dimensional panel with delicate pattern on its surface. This project properly applied the concept of formative fabrication, sophisticatedly controlled where and how much the force needed to be given on the sheet metal.

PROBLEM STATEMENT AND OBJECTIVE

The improvements of CAD/CAM technologies raised the feasibilities of realizing virtual design into physical world. Digital environment and advanced industrial machines are continuously been discussed and applied to various experimental projects, creating astonishing architectural shapes which would have been difficult to create in the past. Nowadays, architects could have more freedom in realizing diversification of architectural performance. However, despite of the rapid growth of expression forms, architects are gradually not satisfied in the computer-aided design processes from common commercially-available software. Due to those predefined functions they limit the creativity of design thinking and ignore the potential of digital computing (Silver, 2006). Besides, different software platforms export their own data format which is difficult to integrate and cause the risk of making mistakes. In the computer-aided manufacturing part, current experimental projects mainly focus on one specific fabrication method. When designers decided fabrication method based on the property of single CNC machine, in the other hand, it limits the multiple possibilities of dealing with material itself. In order to fully exploit the power of digital fabrication, it is necessary for designers to build new design-to-production paradigms in the digital age (Bonwetsch, Bärtschi, Kobel, Gramazio and Kohler, 2007).

Hence, in this research, we aim to establish a synthetic digital fabrication flow which engages with different software platforms and combines vantages from diverse fabrication methods. Through analyzing the preliminary process, we keen to explore the conditions that a synthetic digital design process supposed to have, and the possibility of multiple digital treatments for material.

Methodology

To conduct this research, we set our goal to create a large-scale façade frame system which is built in sheet metal. The reason we chose sheet metal as material is because it can be cut and bent into a variety of different shapes. This property allows designer to apply multiple fabrication methods on it, and gives opportunity for designer to integrate different treatments together. According to this material chosen, in the computer-aided manufacturing part, we took a six-axes industrial robot with welding tool, air compressor and laser cutter as manufacturing media, each device could apply to one specific fabrication method. By cooperation between those devices, we created a new fabrication process which include 2D cutting, additive and formative fabrications together.

In the computer-aided design part, we took industrial software Rhinoceros, CATIA and custom software Unfolded Form KRL as media. Those virtual environments played particular role in the digital process and divided the entire digital flow into three different data making phases which are design data process, construction data process and instruction data process. Following paragraphs would explain the digital flow based on those phases.

Design data process

In this stage, we designed the entire façade system in 3d-modeling software Rhinoceros. By the help of its plug-in software Grasshopper which is an open platform allows designers to script their own modeling tool, we took triangulation method to divide the double-curved geometry into smaller triangular unites. Through the custom scripting tool, every time we adjusted the raw geometry, the script would automatically convert the surface into linear geometry and construct a scheme of triangular frames. The reason we chose triangulation method is that triangle is the most simplified polygon which
could substantially decrease the problem of dealing with angle and position of each components. In addition, this method is a common strategy for 2D fabrication and allows us to approach the freeform surface by rationalized geometry which is efficient for the physical property of sheet metal. After we got an initial scheme of triangular frames, we simulated the inflating result of each component in the digital environment (Figure 5). This step is for analyzing the possible physical result ahead of time, reducing the chance of unexpected outcome. If the simulation is not fulfilled design demand, the raw geometry has to modify again until designer gets expectation result. In other words, we could examine the formative product in the virtual environment to confirm the quality of physical result. Then we stored the location information of each vertex of triangular components in a excel data list (Figure 6). The data did not consider any physical character of sheet metal, but directly recorded the coordinate of each triangle frame that designer created in the digital space. Because it is a simple value list, when we changed virtual platform, the data could directly import to different environment without converting its format.
Construction data process
For the purpose of production, it is important to improve the design data into a feasible data which considered the thickness, bending limitation and other physical properties in the virtual environment. By using CATIA software as a media, we imported the Excel data and gave those digital coordinates some physical meanings, recreating an adaptive virtual model which is fully parametric and built on real production level (Figure 7). Further, we created all adjacent components and connection detail in the digital environment, so we could evaluate the spatial relation between each component for the real space. Thus, if we changed the excel data of one frame, the adjacent triangle models in CATIA environment would be modified as well. Then, through the generative sheet metal design workbench, we separated each triangle frame into bars and unfolded them to get a precise 2D cutting data which included folding lines and inflation holes for further manufacturing. Because all the construction data were produced from the same digital model, it could minimize the risk of making mistakes which are caused by cooperation between different digital platforms. Then, we restored the coordinate of each frame vertex in the CATIA environment, industrial
robot could take that information as welding path to do the repetitive welding task and position each bar to the correct location (Figure 8). Compare with previous step, the digital model at this stage had changed its meaning from simple linear geometry into a model contained physical property of sheet metal.

**Instruction data process**

Although we could record the construction data generated from previous stage, it doesn't represent that industrial robot could directly read the information from CATIA environment. In order to make the robot function, we built a custom software - Unfolded Form KRL to translate the coordinates information in CATIA to robot understanding language KRL code. While the CATIA model simulates the welding process in its virtual environment, the software we built could visualize the same operation system in its interface and export a KRL script for industrial robot. Then the industrial robot would precisely execute welding path and speed according to the script. The design of visualized interface is for designer who has no scripting knowledge to check the production instruction ahead of time, avoiding robot execute wrong movement (Figure 9). By the help of Unfolded Form KRL, we could finally produce the correct instruction command for industrial robot, doing analogical tasks repetitively, and make the fabrication process more efficient and has more possibility.

**Execute fabrication process**

After we got the digital data from previous three steps, all the necessary information for synthetic fabrication is ready. First of all, sheet metal would be treated by 2D fabrication method, cut by laser cutter and produced a piece with unfolded contour of
individual bar. Then, according to the folding line and perforated line we left on the sheet, we could manually fold the sheet metal into correct profile shape without any mechanical force (Figure 10). At this point, each metal bar is still unclosed and needed to weld by robot arm. In order to make this step, we preset a real work bench and let the robot recognize the correspondent location with digital model coordinates. By this way, the entire moving path from KRL script could accurately realize in real world, creating a seamless connection between virtual environment and reality. Then the robot arm located each folded metal piece on the origin of work bench, and welded the opening edges of each component to make a closed bar-shape envelope.

After individual bar accomplished, robot arm would relocate each bar into a correct relationship of triangular frame. Carry on welding the connection parts between each bar and achieved one single triangular frame which is a basic unit of the double-curved geometry. By repeating this process, we could get all the components of the entire design surface. Until this progress, fabrication process took the advantage of industrial robot that efficiently handle large amount of analogical tasks, and produced all the units which are waiting to stack on each other. However, the deflated units are not rigid enough to support the entire structure. Therefore, before stacking all the frames, we took formative fabrication method to inflate each bar by air-compressor. According to

Figure 11
Each bar could bear 7 tons weight without deformation.

Figure 12
Triangular frame done by synthetic fabrication method.
the simulation we did in the design data process, we could certainly know how big pressure that specific bar-shape envelope needed to pump in. Once air inflated the envelope, the inner pressure would increase the space inside of the envelope, making the 1 millimeter thickness sheet metal bar become a rigid structure (Figure 11). After all the components are deformed, we could refer to digital data to install each unit in correct position through layer-by-layer fabrication method. By all the process, we could finally realize the entire double-curved geometry by synthetic digital fabrication (Figure 12).

CONCLUSIONS

For the purpose to incorporate different digital platforms and fabrication methods together, we frequently took custom program that scripted by ourselves to record and export digital data from one virtual environment to another. This phenomenon represents that under the circumstance of developing design and production media, if designers want to fully apply the potential of digital media, the ability of scripting is a necessary condition. And the scripts would have two kinds of trend, one is for creating geometry which is difficult to make by pre-defined commercially-available software. Designers script this program to make the design process more convenient. The other type is collecting data for manufacturing media, especially producing instruction code for various devices. It normally would involve data converting and redefine, and according to the type of fabrication, sometimes the data would feedback to the design geometry for optimization. Hence, scripting would become an indispensable ability in the future, and digital design territory is gradually changing from a subject mainly focusing on how to achieve aesthetic performance to a subject needs to widely absorb different fabrication concepts and programming skills to exploit the potential of design.

By manipulate the synthetic digital fabrication process, sheet metal properties could have more expression possibilities. It shows the material treatment which is synthesized by multiple fabrication process could have more expression potential. Besides, in addition to form finding by CAD environment and precisely manufacturing through CAM process, how to integrate multiple material properties into entire digital flow is a considerable direction. In the future, if the workflow of synthetic digital fabrication process gets more mature, digital design would be able to highly promote the possibility of performance within the same building material cost.

REFERENCES


