HYBRIDIZING DIGITAL FABRICATION TECHNIQUES

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Abstract. The use of digital fabrication in the production and making of architecture is becoming a prevalent vehicle for the design process. As a result, there is a growing demand for computer-aided design (CAD) skills, computer-aided manufacturing (CAM) logic, parametric modeling and digital fabrication in student education. This paper will highlight three student projects that look to ingrate computational prototyping with digital fabrication techniques in the production of architecture. The goal is to hybridize fabrication techniques of sectioning, tessellating and folding to educate students in CAD, CAM, parametric modeling and digital fabrication. Rather than repeating conventional approaches or recreating from precedent, mixing techniques challenges students to understand the CAD technique or parameters for modeling, translate for CAM production and deal with real world constraints of materials, time and tectonics. In the end, these projects are critical of the digital and projectively speculate on the architectural detail in an age of digital ubiquity.

1. Introduction

The digital fabrication techniques we have hybridized emerged from Lisa Iwamoto's book, Digital Fabrications, Architectural and Material Techniques. The professional and academic projects she discusses review fabrication techniques developed over the last decade of sectioning, tessellating, folding, contouring and forming. The book showcases impressive case studies demonstrating "how designs calibrate between virtual model and physical artifact" (Iwamoto 2010). The projects explore the idea of CNC craft and the relationship between the workmanship of certainty and risk and the resistances of making. David Pye's (1971) book *The Nature and Art of Workmanship* introduced us to the concept of workmanship, which according to Luis Eduardo Boza (2006) the workmanship of risk "relies on a personal creative knowledge of the tools, materials and techniques." The design trend that has emerged is evolving the certainty of digital fabrication toward the notion that "we can use digital fabrication as a catalyst for design instead of just a means of production."(Cheng and Hegre 2009) As such, digital fabrication techniques when hybridized provide a creative and critical design process and challenges the notion that the certainty of machine craft removes "risk and the critical creative role of the craftsman/artisan, are taken out of the equation."(Boza 2006)

2. Project Background

Complex, curved and geometric forms in architecture rely heavily on the precise dimensional precision of CAD environments to drive CAM tools. The surface can be a powerful architectural gesture embodying complexity and sophistication. The assignment presented in this paper was interested in the relationship between the building surface and structure as a CAD generated form and a CAM fabricated tectonic. The design process hybridized two fabrication techniques to essentially create a "skin" surface and "bones" structure. At the beginning of this project, two out of three fabrication techniques were assigned to each student: sectioning, folding, and/or tessellating. Students began by referencing these techniques investigating other design projects using the same techniques found in Lisa Iwamoto's book.

Many of the digital fabrication projects directly benefit from the creative application of sectioning, folding or tessellating techniques through exploiting singular operations repeatedly. For the folding technique, projects such as Dragonfly designed by Tom Wiscombe/EMERGENT and Manifold by Andrew Kudless/Matsys both utilized the folding technique to create a hexagonal structure, but were fabricated in very different ways using two different materials. The tessellating technique is exemplified in Living Light designed by Soo-In Yang and David Benjamin and the Puppet Theater by Huyghe + Le Corbusier. While the Puppet Theater aims to rationalize the tessellated surface by using a triangulated panelization, the Living Light dome follows the structure more closely using hexagonal panels for the surface.

The digital fabrication techniques, tessellated parts and folded geometry these projects realized in formal installations, material effects and designs. The projects and installations exploited the laser cut or CNC profiled panels to produce altered visions of surface, structure and space. However, it is in the repetition and scalable variation of similar pieces created through single operations where the techniques become common or normative in their use CNC craft in digital fabrication. "Strategies for articulating the tectonic of NURBS-based envelopes are driven by their geometric complexity" (Kolarevic 2003, p42) and as a result the "rules of constructability" have lead to common geometric rationalization strategies. Along with a discussion on what student's learn, this paper's intention is to highlight the results of hybridizing digital fabrication techniques from Lisa Iwamoto's book and move beyond the normal singular technique of production for new novelty.

The hybridization process is highlighted in three student project examples mutating conventional techniques of sectioning, tessellating and folding. The discussion, which follows, is organized into a short overview of the project, CAM process used in production and a reflection on the fabrication. Each project discusses the opportunities, lessons learned and resistances encountered in the making of each product.

3. BEES KNEES

The first project was inspired by *Manifold* by Andrew Kudless. Bees Knees built on the hexagonal folding technique for the structure and added a triangular tessellation to represent a doubly curved surface. The students used the Rhino CAD software and Grasshopper plug-in to rationalize the honeycomb structure and tessellated surface (Figure 1). Beginning with a flat 16” by 32” surface pushed and pulled control points within that surface to make the object curve in two directions.

Figure 1. Honeycomb folding and tessellated surface.

The students decided to fabricate the structure of the surface first using the honeycomb technique. To develop this structure they applied a *Honeycomb_Basic* script to the surface to get the hexagonal structure output. Then using the *UnrollSrf* command in Rhino to separate the structure into individual strips were laser cut, scored, and folded back and forth to physically fabricate the structure, much in the same way the *Manifold* project was fabricated. Once completed, it was discovered that script used to produce the surface did not account for material thickness resulting in assembly problems. Using a different technique with a Grasshopper definition called *HoneycombCladding* resolved the material thickness issue. This definition rationalizes the honeycombs into cells, similar to the *Dragonfly* project, as opposed to the folded back and forth strips. By using the *ExtrudeCrvPt* command, this produced a series of flat surfaces for each segment of the cell, thereby preventing each member from twisting, which was necessary due to the lack of flexibility of the final fabrication material.

For the tessellated surface, students first manually created triangulated panels on top of the honeycomb structure in the Rhino model, and then again used the *UnrollSrf* command to lay out each triangle in preparation to be cut out of a flat material and applied to the curvilinear surface (Figure 1). After fabricating these pieces, we realized that, due to the flexibility of the structure material, rigidity of the surface material, and triangulation of the surface, the “skin” and “bones” did not perfectly mate. Resolving this involved a triangular surface tessellationg based on the hexagonal shape of each cell.

3.1. CAM PROCESS

The first part of the fabrication process began with using the laser cutter to make our structure (Figure 2). Next, unrolling each surface in Rhino and laying them out within the dimensions of the laser cutter bed (32” X 18”). Each piece was numbered to keep the pieces in order and each segment scored based on which direction it is supposed to fold. Finally, the strips were adhered to the segments that shared a side with one another.

Fig. 2. Student work by Katie Johnston and Kate Sloniker

For the next step, the skin was fabricated using the CNC machine and RhinoCAM to cut out each triangulated piece from a ¼" thick piece of plywood (Figure 2). This proved to not be the best process for fabricating the surface due to the thickness and rigidity of the material and the blunt nature of the CNC machine on smaller delicate pieces. Instead, thin acetate was used on the laser cutter to cut out the triangulated pieces. While cutting the acetate, the heat from the laser caused the pieces to melt back together, which caused the sheet to be more scored that cut. The next issue was how to adhere the pieces to the structure the pieces, which did not line up due to the rigidity of the acetate, and the flexibility of the chipboard.

The final fabrication process incorporated the 3D Printer, which was well suited for the structure (due to its rigidity and accuracy), but was also least economical fabrication process (Figure 2). Also, due to the size requirements of the final product and the limitations of the bed size within the 3D printer, the entire model could not be fabricated using this process. Following several prototypes to rationalize the geometry for the fabrication process of this doubly curved surface, work began on the final model.

To complete this work, a laser cut structure was made from 2-ply chipboard. Next printed-paper templates were cut for the skin to form each cell into its proper shape. After all of the cells were formed, cells were adhered one another to form the doubly curved surface. Next, after removing the paper templates the structure was spray-painted using gray primer and black metallic spray paint. The structure was coated with several layers to give the model a more polished appearance. A connector piece was designed and made from black acrylic, which was laser cut into Y-shaped pieces to join the surfaces at nodes within the structure. Vellum was used as the material for the skin due to its flexibility and semi-transparent character. After also laser cutting and etching the vellum skin pieces they were adhered to the acrylic connectors and the structure.

3.2. FABRICATION REFLECTION

Through this process, students learned that the accuracy of the CAD output for CAM production is not always exact or completely reliable. Material thicknesses can be inconsistent and should be calculated for in the design. In this project, the skin did not allow for any error, students encountered tolerance issues not accounted for in the skin. Allowing more flexibility in the joining of the materials that could accommodate the accuracy of the honeycomb once it has been formed. Additionally, the final spray painted structure deformed the model which caused the final vellum skin pieces to fit catawampus. This resulted in each cell of the bone structure to be readjusted as each skin piece was inserted. As the fabrication progressed, the pieces began to fit more accurately. The reveals in the model showcased the various angled geometry of the structure as it relates to the skin.

4. Space(D) Frame

Fundamentally, Space[D] Frame was a project developed by integrating digital design and manufacturing techniques with rapid prototyping to produce a double-curved surface. The project utilizes the integration of two distinct digital fabrication techniques, sectioning and folding, one for the production of structure and the other for its cladding (figure 3).

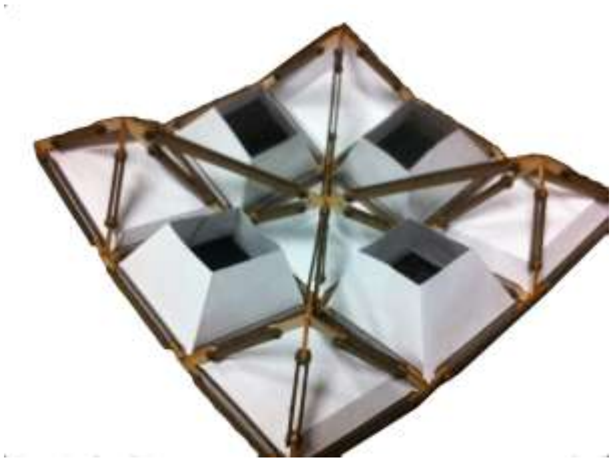

Fig. 3. Skin and Bones prototype

The structure composed of orthographic projections typically used to produce building plans, however, this same technique lends itself to the process of fabrication. Structural grid lines, or ribs, were defined by using a sectioning technique and then extrapolated to define a truss system. An integrating series of joints and members through which the system could be hand-assembled and the cladding integrated further enhances this grid.

The cladding was realized by changing the inherent memory of a material allowing a folded flat surface to define a three-dimensional condition and hold its shape. The cladding enhances the undulations of the surface by exploring the variability of a single-folded system parametrically applied to a double-curved surface. Through a prototyping process, every element of the cladding was integrated into a single unit that could be laser cut and scored.

4.1. CAM PROCESS

To out put the CAM data, a digital model was first created. The inital double-curved surface was divided by a series of iso-curves that were then exported for the development of the structure and the cladding. By the use of precise CAM methods, the structure and skin were digitally and pyhisically produced independently. These tolerences were prototyped so that from the definition of the intial iso-curves, the stucture and the cladding did not need to be joined until the final physical assembly, where each part seamlessly integrated into the other to the degree that previously designed structural elements could be replaced by the rigidally folded cladding units.

To begin the intensive design and iteration process the structure was first tested in its relation to a flat plane. By simplifying the structure to such an extreme degree, complex elements of the design could be thought about first in simplfied conditions before being defined with more complexity. The sectioning technique and structural pattern were then digitally applied to a double-curved surface. This was then prototyped, which produced a simple cardboard model that was developed with members that span the full length of the model. Although it effectivly produced a double curved surface, it was lacking in cladding and an elegant system of production. A skin soon began to populate the structural units of the prototype by folding units over its members. The prototyping process then began to focus on the cladding units and how they were able to occupy the built surface. In turn, this identified the need to better integrate the two disticnt systems. Simultaneously, the structure and cladding developed at a staggering pace. The structure was divided into members and joints and the cladding's folding systems began to become more defined as enhanced ways of folding the units emerged. The joints became the connections between the cladding and structure and a iterative refiniment of the stucture began. With each iteration complexity and elegance were gained. Several member and joint stratigies were defined, and the result produced a series of uniform joints and custom members that formed the structure, as well as a system of custom joints and semi-uniform members that connected to the cladding. These members were eventually fully integrated into the cladding, and for the final surface only, exist on the perimeter of the design to create a finished edge.

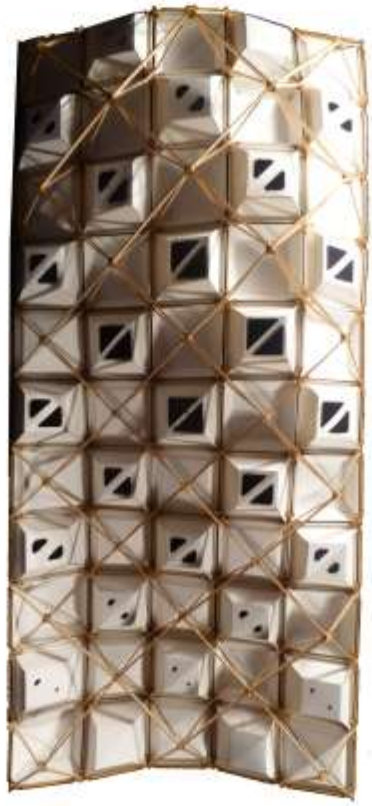

Fig. 4. Skin and Bones final prototype

4.2. FABRICATION REFLECTION

The design intent, although realized through a highly iterative process, was to create a digitally produced double-curved surface with a physical model composed of two parts: the bones or structure of the surface and the skin or cladding of the surface (figure 4). By heavily utilizing CAM software, in this case Rhino and the Grasshopper plug-in, multiple techniques were explored on-screen before material was ever cut to manufacture. Through the use of digital software, a high level of design collaboration was achieved in moving between design of structure and skin, thereby achieving high tolerances when moving in the manufacturing phase. Critical in this digital exploration were design of the structural joints as well as the folding technique of the skin.

5. Fluid Weave

The intent of this design was to creatively explore and push the limits of a doubly curved surface in both the terms of computer generation and fabrication. The surface or “skin” manifested itself using a process of folding while the structure or “bones” was formed through tessellation. The more complex system of the structure is composed of two independent hexagonal tessellations that weave in and out of one another. The two are joined together using supports located at common points where the two grids overlap vertically. Folding sections of flat material was used to create a more rigid and three-dimensional surface for the skin.

5.1. CAM PROCESS

Our inspiration for the design came from Hyoung-gul Kook, who had previously designed interweaving geometric patterns. This was the initial inspiration for the structure and its weaving character. The challenge students pursued were how to generate the form within Grasshopper and then manipulate it to fit the expectations of the assignment. Beginning with an image of his work, the approach was to translate this into grasshopper and create a form that was three-dimensional and would conform to the constraints imposed by physicality in the real world. The grasshopper definition developed was able to define a variety of parameters that had to be set in order to develop the structure, which was applied to a doubly curved surface.

One consideration of digital design was deciding how the double-weave hexagonal parts would interact to create a structure. The digital realm allowed for the creation of a form that held its shape and position without any connections or technical feasibility. Grasshopper’s parametricism allowed this problem to be solved by simply creating shafts that connect points between the double-weave. This saved time in the initial model prototype but also created different variations of doubly curved surfaces and sizes of tessellations to divide the grid. Finally, after much iteration ranging from pure geometric forms to complete fluidity resolution on the final model satisfied the students’ aesthetic sense, while remaining within our means of fabrication.

5.2. FABRICATION REFLECTION

After multiple failed attempts with the CNC router we decided to fabricated the pieces using the 3D printer because of the high degree of accuracy it can produce. This brought about its own set of chalenges due to the brittle nature of the material. One technique that helped to counter this was the use of color which not only allowed us to deduce the position of each piece but also strengthen the 3D print.

The skin presented its own set of chaenges. It was intended that the cladding be planar, making it easy to cut out and assemble. The dificulty in the output was creating a polysurface out of a flat piece of material. In the end, the surface which was cut out of bristol on the laser cutter, required the edges to be scored, making it easier to fold the material into a three dimensional shape.

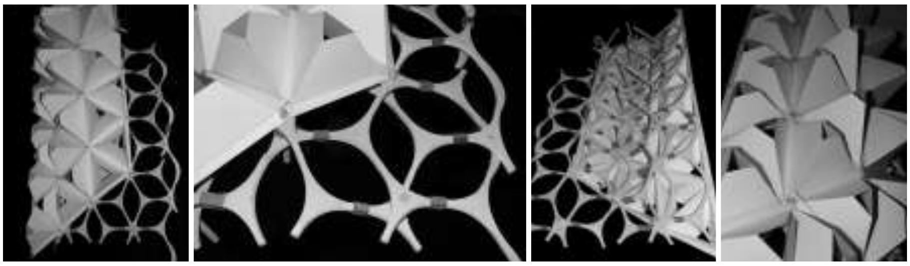

Fig. 5. Fluid Weave project showing structure and skin detail.

Examining the final model, Figure 5, techniques of tessellation and folding can be identified in the structure and skin. Additionally, an effect of transparency begins to appear as the fenestration of the skin's panels change according to a curvature of the base surface. Although very ethereal, the model itself functions successfully, as the skin could not hold its shape without the support of the structure behind it.

The output of the final model taught students about margins of error as well as the importance of calculating and compensating for the inaccuracies of the human hand. Though the pieces of our structure were highly precise, human error in assemblage produced misalignment between parts that multiplied across the surface. In addition, constraints of material also made matters of construction difficult. With each failed iteration and unsuccessful model there came a learning experience. This taught students the importance of prototyping and its function in the real world.

Digital fabrication, much like architecture, truly is an iterative process of thinking, making, and rethinking. There is no straight line from conception to final product. Even if a first attempt is successful, one must always contemplate on how to further optimize the process in order to achieve higher quality, a quicker process or a cheaper means of fabrication.

6. Conclusion

Emerging digital technologies were used throughout these projects to projectively construct architectural details. The digital integrated design and production, where the agency of the detail is formed and informed by the unexpected resistances inherent in the design process. For example, the resistance of the materials used, the fabrication machines, the software output and the translation of CAD designs, via file-to-factory, for CAM production provided critical agency upon both the digital and the detail.

The three projects all succeed in incorporating sectioning, tessellating and folding techniques in their projects. The first project, Bees Knees, highlighted a meticulous rationalization process of the double-curved surface into a skin and bones hybridizing a folded structure with a tessellated surface. While this project expanded the honeycomb script to include a triangular tessellated surface, the techniques did not result in anything particularly different. Next, the Space(D) frame project did depart from conventional sectioning techniques, producing a double parallel space frame structure for folded tessellated inserts. The folded inserts were novel in the sense of the realization of variation and adaptation to resolve the curvature of the overall form. Each piece contains a similar genome, but must evolve to each site situation within the structure. Additionally, the structure adapted to the inserts inherent folded structural capacity. The folds provided enough rigidity that not all the structural cross members were needed, allowing the skin and bones to dissolve into one cohesive structure.

Finally, the Fluid Weave project was successful in a double-hexagonal tessellated weave for the structural bones. Success relied heavily on the 3d printer to additively construct the complex forms. However, the overall folded surface failed to integrate into this underlying structural complexity.

As Branko Koleravic has described, “Designers are constantly looking for particular *affordances* that a chosen production method can offer, or unexpected *resistances* encountered…” (Koleravic, 2008, p127). Through integrating CAD design, CAM logic, parametric modeling and hybridized techniques of production afforded opportunity to create something other. The student projects and descriptions in this paper describe how creatively leveraging the CAD/CAM process for design departed upon the resistances encountered in the materials, tooling, and file-to factory process. Critical to their success was the rapid prototyping capabilities of the 3d printer and the iterative file-to-factory process engaged to produce multiple models. Those projects, which were quickest to iterate through physical models encountered - agency of the detail - the unexpected resistances affording - agency of the digital - them the opportunity to design eloquent solutions.

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