ITcon

www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

USING PROTOTYPING TO TEACH DIGITAL FABRICATION TECHNIQUES

REVISED: July 2012
PUBLISHED: September 2012 at http://www.itcon.org/2012/19
GUEST EDITOR(S): Bhzad Sidawi and Neveen Hamza

Timothy L Hemsath, AIA
College of Architecture, University of Nebraska-Lincoln;
themsath3@unl.edu and architecture.unl.edu

SUMMARY: *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 modelling and digital fabrication in student education. This paper will highlight a case study project that sought to ingrate computational prototyping with digital fabrication techniques in the production of architecture. The goal is to use virtual and physical prototyping to educate students in CAD, CAM, parametric modelling and digital fabrication. Rather than repeating conventional approaches or recreating from precedent, iterative prototyping challenges students to understand the CAD technique or parameters for modelling and translate intentions for CAM production. Students engage real world constraints of materials, time and tectonics. In the end, these projects are critical of the digital and speculate on the architectural detail in an age of digital ubiquity.*

KEYWORDS: Digital Fabrication, CAD/.CAM, Prototyping

REFERENCE: *Timothy L Hemsath (2012) Using Prototyping to Teach digital fabrication techniques, Journal of Information Technology in Construction (ITcon), Vol. 17, pg. 300-307, http://www.itcon.org/2012/19*

1. INTRODUCTION

Digital fabrication techniques emerge 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 sectioning, tessellating, folding, contouring and forming. The book showcases impressive case studies demonstrating "how designs calibrate between virtual model and physical artefact" (Iwamoto 2010). The projects explore the idea of Computer Numerical Control (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." CNC craft, one CAM tool, represents both a workmanship of certainty in the precise numerical control used for manufacturing and risk in how students creatively leverage this certainty to produce a prototype. Therefore, in the prototyping activity is the resistance of the tool in how it is used, the resistance of materials as they are subject to the tool to produce the prototype.

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 provide a creative and critical design process and challenges the notion that the certainty of machine craft removes the "risk and the critical creative role of the craftsman/artisan, are taken out of the equation."(Boza 2006) Instead, digital fabrication elevates the creative power of making leveraging the certainty with the creative affordances inherent in risk.

Dimensional precision of CAD environments that drive CAM tools is necessary for creating complex, curved geometry and architectural surfaces. The surface can be a powerful architectural gesture embodying complexity and sophistication. The following projects explore the relationship between building surface and structure as a CAD generated form and a CAM fabricated tectonic. The design process used two fabrication techniques to create a "skin" surface and "bones" structure. To start the design each student used two out of three fabrication techniques: sectioning, folding, and/or tessellating. Students referenced these techniques and investigated other design projects based on 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 fabricated in very different ways using two different materials. The tessellating technique exemplified in Living Light designed by Soo-In Yang and David Benjamin and the Puppet Theater by Mos with Huyghe. While the Puppet Theatre 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 formal installations and material effects represented in these designs evolve from digital fabrication techniques, tessellated parts and folded geometry. The projects and installations exploited the laser cut or CNC profiled panels to produce altered visions of surface, structure and space. However, in the repetitive and scalable variation of similar tessellated pieces created with a single operation is how digital fabrication techniques become common or normative in their use of CNC craft. "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. The author's intent is to highlight the results of virtual and physical prototyping based on digital fabrication techniques from Lisa Iwamoto's book; to discuss their applicability to real world architectural. A summary of student project results terminate each section following a discussion on what the students learned in the completion of the project.

Three student project examples, previously discussed by Hemsath (2012), mixed the conventional digital techniques of sectioning, tessellating and folding as explorations in CNC craft. This paper is an updated and revised version of the paper that was presented at ASCAAD 2012 conference (Hemsath 2012). The revision highlights how the act of virtual and physical prototyping informed the final product. The act of making using rapid prototyping (RP) techniques is common within the design/manufacturing industry. CAD/CAM techniques offer a quick and accurate way to prototype ideas with relatively low cost and exactness at a particular scale and detail (Sajid et al. 2006). The organization of the discussion that follows begins with a short overview of the project, discussion of the CAM process used in production and a reflection on the prototyping lessons.

2. BEES KNEES

The first project inspired by *Manifold* by Andrew Kudless is a large-scale honeycomb wall. 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 Rhinoceros CAD software and a Grasshopper plug-in to rationalize the honeycomb structure and tessellated surface to create a virtual prototype (Figure 1). Driving the design began with a flat 16" by 32" surface pushed and pulled control points within that surface to make the object curve in two directions.

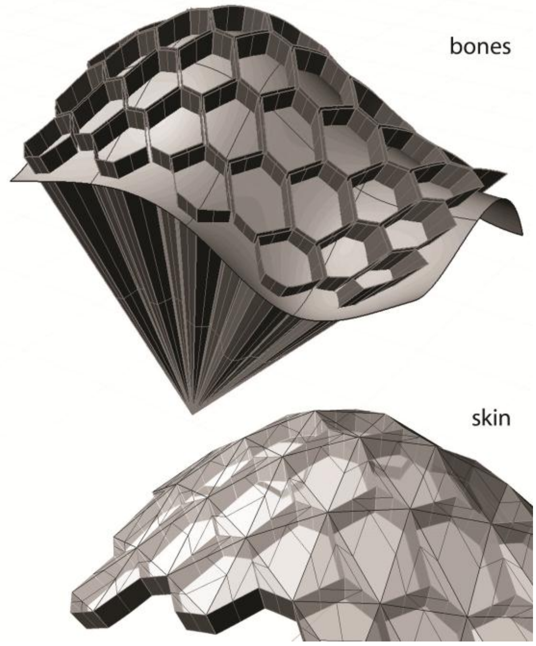

FIG. 1: Bees Knees first virtual prototype of structure (above) and surface (below).

2.1 CAD Process

The students decided to virtually prototype the structure and the surface using a honeycomb technique. From the virtual prototype a section was selected and 3d printed to create a physical prototype. To develop the structure they applied a packaged script, *Honeycomb_Basic*, to the surface to get the hexagonal structure output. Then using the rhinoceros *UnrollSrf* command separated the structure into individual strips for the laser cutter. These pieces were lasercut, scored and folded back and forth to physically fabricate a paper mock-up of the structure; much in the same way the *Manifold* project was fabricated. Once completed, students discovered the 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 when considering real world application with flat stock materials.

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 2, right). After fabricating these pieces, 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 tessellation based on the hexagonal shape of each cell.

FIG. 2: Bees Knees virtual prototype (left) 3d printed prototype (center) and paper mock-up (right).

2.2 CAM Process

The first part of the fabrication process began with using the laser cutter to make the structure (Figure 3). Next, unrolling each surface in Rhino and laying them out within the dimensions of the laser cutter bed (32” X 18”). To keep each piece in order they were individually numbered 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.

The final fabrication process incorporated the 3D printer, which was well suited for the structure due to its rigidity and accuracy (Figure 2, center). Using the 3D printer is not practical for producing the entire model due to the size requirements of the final product and the limitations of the 3D printer bed size. Following several prototypes to rationalize the geometry for the fabrication process of this doubly curved surface, work began on the final model.

FIG. 3: Bees Knees honeycomb cells.

To complete the project, the laser cut 2-ply chipboard to form the cellular honeycomb structure. After each of the folded cells turned into their final shape (Figure 3), each cell joined with its neighbour to form the doubly curved surface. The chipboard structure coated with several layers of grey primer and black metallic spray paint gave the model a more polished appearance. A Y-shaped connector piece cut from black acrylic joined the skin at nodes within the structure. Each cell’s printed-paper template formed the proper shape of the skin. The skin used vellum as the material for to its flexibility and semi-transparent character. The laser cut and etched skin pieces for folding before being adhered to the acrylic connectors and the structure.

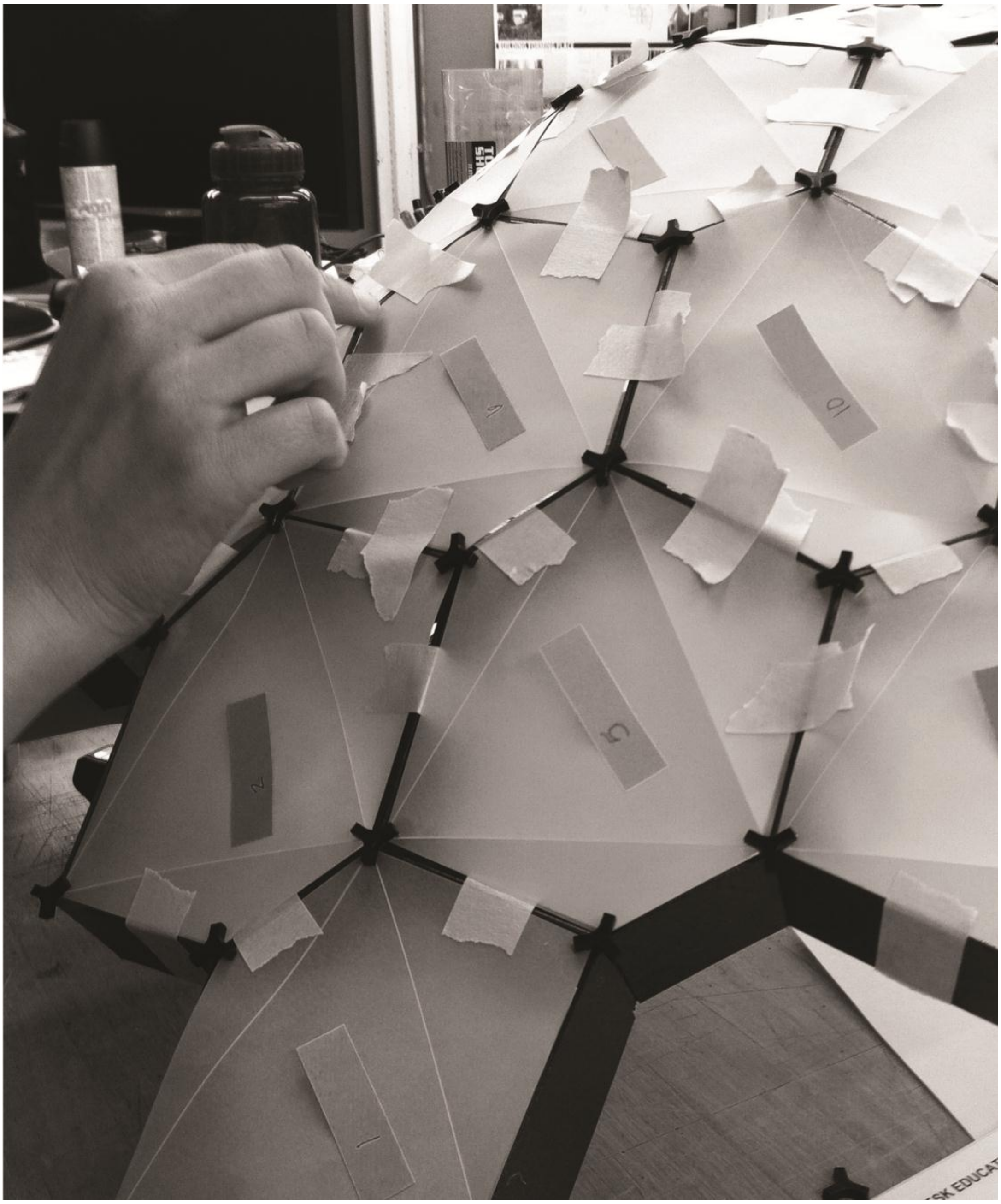

FIG. 4: Bees Knees construction of final product.

2.3 Prototyping Lessons

Through this process, students learned that the accuracy of the CAD output for CAM production is not always exact or completely reliable. The virtual prototype resolved larger design issues of form and structure. When the virtual became physical issues of geometry, material and machine craft were foregrounded as production flaws. These discrepancies between virtual intention and physical artefact were resolved through the iterative prototyping process. The making of and the final physical product informed alterations to the virtual model.

Understanding the geometry of the artefact produced is both a virtual and physical exercise. How one creates an object within a virtual environment is not a one to one relationship with the physical production methods. As observed in the making of Bees Knees, several CAD routines explored methods to virtual prototype solutions before producing a workable for laser cut file. Within this exploration, the virtual prototype evolved to suite the laser's two-dimensional CAM production technique.

Material lessons related to inconsistent thicknesses and production outcomes affected the design. One failed prototype encountered was when the triangulated piece of skin cut from ¼" thick plywood. Students used RhinoCAM to generate the g-code. Using the 3-axis CNC machine was not 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, students used the laser cutter to cut out the triangulated pieces of thin acetate. 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 skin components to the structural members, which did not line up due to the rigidity of the acetate, and the flexibility of the chipboard. In this project, (figure 3) the CNC precision used to manufacture the skin did not allow for any error. Students encountered tolerance issues in the connections between the skin and cells and needed to allow for more flexibility in joining of the skin material to the cellular geometry of the honeycomb. Additionally, the final spray painted structure deformed the model, which caused the final vellum skin pieces to fit slightly twisted. This resulted in each cell of the bone structure to readjust as each skin piece as inserted. As the fabrication progressed, the pieces began to fit more accurately. The reveals in the model highlight the various angled geometry of the structure as it relates to the skin.

The machine 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. These lessons teach students about 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 and a more economical means of fabrication. The design intent, realized through a highly iterative process, created a digitally produced double-curved surface as a physical model composed of two parts: the bones or structure and the skin or cladding both defined by the surface. By heavily utilizing CAM software, in this case Rhino and the Grasshopper plug-in, multiple techniques explored solutions virtually before manufacturing the material. Using digital software requires a high level of design collaboration oscillated between designing the structure and skin, thereby achieving high tolerances when moving in the manufacturing phase.

FIG. 5: Bees Knees final product completed by students Kate Sloniker and Katie Johnston.

3. CONCLUSION

CAD/CAM technologies used throughout this project constructed architectural surface and structure details. Digital fabrication integrates design process with production through the various prototypes. The unexpected resistances embedded in making prototypes formed and informed student learning. 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 making and the production.

The project succeeds in incorporating sectioning, tessellating and folding techniques. The Bees Knees project highlighted a meticulous rationalization process of the double-curved surface into a skin and bones hybridizing a folded structure with a tessellated surface. Bees Knees expanded the honeycomb script to include a triangular tessellated surface into the cellular structure. Additionally, the structure adapted to the inserts inherent folded structural capacity. The folds provided additional for the structural honeycomb members, allowing the skin and bones to dissolve into one cohesive structure. Through combining digital fabrication techniques as part of a prototyping exercise the normal singular production techniques become integrated into the design process affording unexpected opportunities.

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 modelling and prototyping techniques of production afforded opportunity to create a highly coordinated final product. The student project and description 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 the projects success was the rapid prototyping capabilities of the 3d printer and the iterative file-to-factory prototyping engaged to produce multiple models. Teaching digital fabrication uses iterative prototyping of physical models to explore the agency of the detail and the agency of the digital. CNC craft embraces the unexpected resistances affording an opportunity to execute eloquent solutions that have departed from repetitive singular operations into something more.

4. REFERENCES

Boza, L. E., (2006). (Un) Intended Discoveries Crafting the Design Process. In Proceedings of the 25th Annual Conference of the Association for Computer-Aided Design in Architecture, eds. Luhan, G. A., P. Anzalone, M. Cabrinha, and C. Clarke. p150-157.

Cheng, N-Y and Hegre, E., (2009). ‘Serendipity and Discovery in a Machine Age: Craft and a CNC Router, In Proceedings of the 29th Annual Conference of the Association for Computer Aided Design in Architecture, Chicago, Illinois.

Hemsath, T., (2012). Teaching Digital Fabrication Techniques. *InForm Journal,* vol. 11: 38-51.

Iwamoto, L., (2009) *Digital Fabrications: Architectural and Material Techniques*. Princeton Architectural Press, New York, NY. P4-7.

Kolarevic, B., (2003). “Digital Production” in *Architecture in the Digital Age: Design and Manufacturing*, Branko Kolarevic, ed., New York, NY: Spon Press.

Kolarevic, B., (2008). “The ‘Risky’ Craft of Digital Making” in Manufacturing Material Effects Rethinking Design and Making in Architecture, Kevin Klinger and Branko Kolarevic, ed., New York, NY: Routledge.

Pye, D., (1971). *The Nature and Art of Workmanship*, London, Studio Vista; New York, Van Nostrand Reinhold.

Sajid, A., Marasini, R., and Ahmad, M., (2006). An Analysis of the Applications of Rapid Prototyping in Architecture, In the Proceedings of Computing in Architecture / Re-Thinking the Discourse: The Second International Conference of the Arab Society for Computer Aided Architectural Design (ASCAAD 2006), 25-27 April 2006, Sharjah, United Arab Emirates.

This paper is available electronically at http://itcon.fagg.uni-lj.si/~itcon/index.htm