DIGITAL DESIGN AND FABRICATION TECHNIQUES USING A 3-AXIS CNC MILL

A Senior Scholars Thesis

by

KY ROBIN COFFMAN

Submitted to the Office of Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

April 2010

Major: Environmental Design

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Research Advisor:	Gabriel Esquivel
Associate Dean for Undergraduate Research:	Robert C. Webb

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ABSTRACT

Digital Design and Fabrication Techniques Using A 3-Axis CNC Mill. (April 2010)

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The objective of my research involves an investigation of the relationship between design and production through a case study fabrication project which utilizes digital design software and manufacturing technologies, to achieve a better understanding of where formal, spatial, and material possibilities lie. This project focuses specifically on using CNC (Computer Numerical Control) fabrication techniques to produce three-dimensional forms with poly-urethane foam aimed at achieving certain surface effects and material sensations. Critical to understanding the potentials of digital fabrication is an understanding of its evolution to its current role in contemporary architecture. My methods consist of a qualitative approach to the evolution of digital design tools and manufacturing technologies. I have conducted a thorough literature review and will provide an overview of concepts surrounding the digital paradigm such as materiality, sensation and affect. Secondly, a fabrication project was completed from design to production using a three-axis CNC mill, our current machine at the Texas A&M Architecture Ranch. Three-axis CNC mills are typically used to create surface effects

and not completely three-dimensional objects because of their inability to rotate out of the *z*-axis to make undercuts. We investigated different fabrication techniques that can be used to create completely three-dimensional forms with this machine and poly-urethane foam. Included in the fabrication process was extensive material research as to which additive materials were best able to increase the foam's surface strength and smoothness and provide appropriate finishing to produce a liquid-like effect. A sectioning technique using cuts in both the horizontal and vertical direction was developed and can serve as an example of a possible means of fabricating large scale three-dimensional forms with a three-axis mill. A machine with a great number of axes, four or five, would greatly cut down on material costs, as well as fabrication time and complex assembly and finishing techniques.   We hope that this project will help encourage experimentation and research in the area of digital fabrication as contemporary architecture moves forward to a complex digital profession.

ACKNOWLEDGMENTS

I would like to take this opportunity to thank my research advisor Professor Gabriel Esquivel for his perpetual support and enthusiasm throughout this and other projects. I will forever be grateful to him for introducing me to the world of digital design and fabrication and sharing his vast knowledge, experience, and visions with me. Matthew Richardson and Jeffrey Quantz were integral to the fabrication of this project and their hard work was truly invaluable. Jeffrey's photography skills were essential in order to document the various stages of the work. This project would not have been possible in the first place if it were not for the design by Professor Esquivel and Chris Gassaway, and I thank them for giving me the opportunity to share in the realization of their design. I would also like to thank Dr. Mark Clayton for sharing his knowledge of research methods with me and for his support of undergraduate research. The funding provided by the College of Architecture and the Undergraduate Research Scholars Program is greatly appreciated.

NOMENCLATURE

CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CNC	Computer Numerical Control
CATIA	Computer Aided Three Dimensional Interactive Application
IGES	Initial Graphics Exchange Specification
NURBS	Non-Uniform Rational B-Splines

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CHAPTER I

INTRODUCTION

Digital media and emerging technologies are bridging the gap of design and production allowing for a more fluid translation of digital models to three-dimensional production through CNC machines, laser cutters, and 3D printers, among many others, thus rapidly expanding what we conceive to be formally, spatially, and materially possible (Iwamoto, 2009). The objective of my research is to examine the relationship between design and production through a case study fabrication project which utilizes digital design software and manufacturing technologies, in order to achieve a better understanding of where the formal, spatial, and material possibilities lie. Branko Kolarevic states that “each new experiment and each new collaborative pursuit will help broker change as projects move towards redefining techniques and methods of design conception and material realization.” (Kolarevic, Klinger, 2008). The fabrication project we completed, *Malbec*, employed extensive material research and we found that by challenging the properties of a traditional building material, poly-urethane foam, we were able to achieve better surface performance, and produce certain material effects. The specific methods and fabrication techniques used were thoroughly documented and analyzed, and we believe they can serve as an innovative example of the possibilities of what can be done using these technologies.

This thesis follows the style of *Journal of Architectural and Planning Research*.

For the purpose of this study, digital fabrication can essentially be defined as the manufacturing of building components directly from 3D computer data. It is a process that lies within the scope of computer-aided design and manufacturing (CAD/CAM), and relies on computer-driven machine tools to build or cut parts (Iwamoto, 2009).

History

In the past, Euclidian geometric construction procedures defined the limits of shape generation possibilities for architects, and was a rather long and laborious hand drafting process. Originally used as a mere presentation tool, early CAD technologies allowed for greater efficiency in terms of cost, time, and quality control for designers, but the shapes that were generated remained ultimately the same. Designers eventually began to expand on this tool, and began defining curved forms and surfaces with mathematical functions, which greatly expanded the shape universe (Mitchell, 2008). Essentially, as digital modeling software became more advanced, the forms that generated became more increasingly more advanced and complex. Software became not just a presentation tool, but a design tool as well, allowing architects to design irregular surface patterns and complex forms and CAM tools gave them the ability to actually produce them exactly as they were modeled. These technologies are opening the door to experimentation with new architectural aesthetics, and the production of affective, experiential atmospheres able to evoke emotional responses.

The manufacturing, engineering, and industrial design industries have been using CAD/CAM software for years, allowing for fluid transitions between design and efficient mass-production of standardized parts. They used 3D modeling software and computer numerical control technologies (CNC) which allow automated equipment to be controlled and operated in real time through the use of manufacturing programs that translate digital data into a language that the machine can understand. Although these technologies have been around for years, it is only within the past couple of decades or so that they have began being applied to contemporary architecture. The ability to mass-produce irregular building components within the same facility as standardized parts introduced the notion of differentiation into building design and production. It is now just as efficient and cost-effective for a CNC milling machine to produce thousands of unique objects as to produce thousands of identical ones (Reffat, 2008).

Malbec

The digital fabrication tools used in our project *Malbec*, included the digital modeling tools: Autodesk Maya and Rhino, the manufacturing software, MasterCAM, and our machine used was a 3-axis CNC (Computer Numerical Control) machine. Material removal is the essential characteristic of subtractive fabrication, and is generally a CNC milling technique. 3-axis CNC machines are the most common type of machine and allow for movement in the *x*, *y*, and *z* axes, therefore only allowing material to be removed from the top and sides. As the number of controlled axes increases, the complexity of the work that can be produced also increases (Schodek et al. 2005).

Machines with axes greater than 3 have the ability to make undercuts because the head holding the bit is able to rotate out of the *z*-axis. Since we were limited to using a 3-axis machine, the most challenging part of the fabrication process was to devise a technique that allowed us to mill and assemble the 3D portion of the design.

Research questions

Malbec addressed material experimentation with poly-urethane foam to produce expressive form. We strove for minimal design sacrifice by developing innovative fabrication techniques and assembly procedures which allowed us to find a way around the machine limitations. We were interested in how to create certain surface effects and increase material performance by combining the foam with additive materials including films, lacquers, and coatings. *Malbec* deals with issues such as architectural experience and it engages the scale of the human body. It can be perceived as an object as well as experienced as a sensate architectural environment.

CHAPTER II

METHODS

This research project utilized both a qualitative and quantitative method. The first being a categorization of the main themes identified in literature, and the second being the implementation of a digital fabrications project, *Malbec*, which included extensive material research and an investigation of material effects. I have taken a historical/interpretive approach to the literature and tried to organize it in a way that is cohesive and comprehensive to give a broad overview of very complex concepts surrounding contemporary digital design. In addition to the literature review, I have identified prior research concerning fabrication projects being done at academic institutions, including information from my visit to the digital fabrications facility at the Georgia Institute of Technology. It is important to have an understanding of the research being conducted at other prominent universities and the technologies being used in order for A&M to remain competitive in this fast-growing area of digital design. The second part of this thesis involved the actual fabrication from design to production of a project, *Malbec*, which utilized the manufacturing tools available at Texas A&M. This portion of the research has fostered the most results, enabling me to apply knowledge gained from the literature to the actual project implementation. *Malbec* was designed to be a prototype for a digital storefront that uses rustication as its articulation.

Methods

It is important to note that this project has not been undertaken solely by me, but with a collaborative group of other students and my advisor, Gabriel Esquivel. The project was fabricated by professor Esquivel, Matthew Richardson, Jeffrey Quantz, and me. While Chapter IV deals with our actual techniques and fabrication processes used, the basic method after completion of the design included file preparation, manufacturing, assembly, and finishing. Our data collection dealt with material experiments and an evaluation of the properties of materials, how they behave with different additive media, and what sizes, strengths, etc. were appropriate.

Analysis

A major part of the research was the analysis and documentation portion. Each step taken, and experiment done was documented to provide conclusions as to which processes, materials, techniques work together and which do not. The documentation provides the sequential set of step-by-step procedures that were used in each fabrication process. Some of the steps had possible alternative solutions and these issues have been addressed to the best of my ability. I have tried to present this information in a way that, people not familiar with digital design and fabrication can easily understand. Simultaneously, any person following each set of step-by-step procedures should be able to achieve the same results. It is important to note that each project is unique in and of itself and each requires separate evaluations of appropriate materials and fabrication processes. The techniques we provide are meant to serve as an example of one possible solution to the problem of fabricating three-dimensional form using a 3-axix CNC mill however, there are alternative solutions.

Materials and technological resources

Since this project was carried out from design to production, it was important to be critically aware of our available production tools, and material possibilities early on in the design process. I believe that the evaluation each software, hardware, and analog tool was crucial to the success of this project. Every tool has a purpose, but that purpose should be continually challenged to foster new techniques and more innovative design solutions. Our primary software resources were Autodesk Maya and Rhinoceros, both of which were used back and forth for the design and file preparations. As mentioned earlier, we were confined to using the available production resources here at Texas A&M. The Architecture Ranch was our prime workspace, as they have a 3-axis CNC router, and other traditional woodshop machines, as well as the space needed to fabricate this large scale project.

Limitations

This project is limited in terms of generality, since each fabrication is project-specific and most likely cannot be applied to a broad range of design problems. It does however maintain a higher degree of reliability especially because the documentation is compiled as step-by-step narrative. Anyone that follows these exact steps should be able to achieve the same results, therefore verifying that what I have provided is reliable. The availability of a CNC mill with a greater number of axes of rotation would allow for a much faster fabrication time and could have greatly simplified our assembly process, as well as cutting down on material waste. We believe that it was important to not allow the restrictions of the machine to limit the complexity of the design. Instead, we focused on finding innovative solutions that allowed us to deal with these limitations in a creative way and not sacrifice the integrity of the design. I believe that this was legitimate research project because “each new experiment and each new collaborative pursuit will help broker change as projects move towards redefining techniques and methods of design conception and material realization.” (Kolarevic, Klinger, 2008). Each new project is unique and will add to the collective body of knowledge concerning this relatively new and rapidly expanding field of design.

CHAPTER III

LITERATURE

This section focuses on the major themes identified in literature concerning contemporary digital design, theories, the evolving role of the architect, and prior research. It is meant to provide an overview of concepts, many of which influenced the production of *Malbec*.

Industry collaboration

The age of mechanical production, of linear processes and the strict division of labor, is rapidly collapsing around us. (Mori, 2002) The move from an architectural discipline of experts to a more multi-disciplinary field involving inherently collaborative ways of working is literally turning on its head a conventional and familiar modern business expectation of architectural practice. (Steele, 2008) The role of the architect in contemporary architecture becoming redefined and digital fabrication allows for the architect to regain their role as the master builder. Because the architect now has the opportunity to command control over both the design and construction processes and through collaboration with industry experts, projects are instilled with a higher level integrity. Brett Steele identifies the greatest challenge in architecture today as being the need for multi-disciplinary expertise within design teams. Architectural projects today collaborate between computer programmers, machinists, artists, composite material engineers, laser cutters, rubber workers, new media animators, mathematicians, etc… all immeasurably more advanced than that of conventional construction and manufacturing trades. (Steel, 2008) This collaboration between experts in seemingly unrelated fields employs a higher degree of innovation and integration into projects than ever before. Projects are able to be much more complex because they have the ability to extend across multiple areas of design expertise.

Unique practices geared towards facilitating design and construction processes of new formal complexities and tectonic intricacies are establishing themselves as a result of this newfound need for industry collaboration. (Kolarevic, Klinger, 2008) Innovative practices like *Front Inc.* from New York, *designtoproduction* from Zurich, *3form Inc.* from Salt Lake City, and *Associated Fabrication* developed by graduate students from Colombia University, have emerged as a kind of fabrication specialists, translating the needs of designers in to actual physical artifacts. Rather than spending hundreds of thousands of dollars investing in expensive CNC machinery, architecture firms are contracting out their fabrication projects to these recently established fabrication-specialist's shops. In his paper, "Design Intelligence and the New Economy" Michael Speaks discusses the evolving roll of the architecture firm as a new "network practice" involving a complex series of geographical, functional, and formal relationships, ideas and information. He defines design intelligence as practices that allow for a greater degree of innovation because they encourage opportunism and risk-taking rather than problem solving. He argues that research is an essential ingredient for designing in the context of the 21st century. (Speaks, 2002).

At a smaller scale of the actual project implementation, there is collaboration between the digital model, fabrication process, and typically the finishing or assembly process. Digital fabrication allows for a simplified construction process because often the need for traditional building plans and sections is eliminated. Instead, fabricators navigate back and forth between the digital model and physical parts, or rely on diagrams that visually illustrate how pieces fit together. Because of this unique method of construction, there is potential for each process to inform and be informed by each other, thus altering the traditionally separate roles of the architect, contractor and construction manager. I believe there is great potential for innovation to occur within the gaps between these processes.

Materiality

As a result of the ability to design and construct fundamentally complex geometries, there has been a renewed interest by designers in materiality. Conventional construction materials are being re-invented and applied in unconventional ways, and also there is an emergence of new materials, with the ability to be engineered with per formative qualities, able to produce new effects. The emergence of new techniques and methods of digitally enabled making are “reaffirming the long forgotten notions of craft, resulting from a desire to extract intrinsic qualities of material and deploy them for particular effect.” (Kolarevic, Klinger, 2008) Of particular interest are “new” composite materials, such as polymers (plastics), fiberglass, and foams, for their high formability, relatively low cost, minimum maintenance, and a relatively high strength-to-weight-ratio. (Kolarevic and Klinger, 2008). One of the results of these new material experiments is that material is no longer a fixed entity, but rather quite changeable. Since materials are no longer employed for purely functional reasons, the innovative, experimental use of them is encouraged and even pushed to the most extreme limits. For instance, plastic can now be made to look like metal and vice versa; therefore materials and the effects they produce are apt to change based on the nature of their context. (Spina, and Huljich, 2009).

Material sensations

The issue of materiality cannot be addressed without addressing the consequences thereof. As with all historical technological advances, the flux of digitally enabled making is being reflected in the architectural aesthetics of our generation. These aesthetics are concerned more with the experiential and affective qualities rather than modernism ideals of order and function. It is important to differentiate between the terms *effect* and *affect*. According to Peter Eisenman, *effect* refers to "something produced by an agent or cause; in architecture, it is the relationship between some object and its function or meaning." Simultaneously, he defines *affect* as "the conscious subjective aspect of an emotion considered apart from bodily changes. Affect in architecture is simply the sensate response to a physical environment". (Eisenman, 1992). So in other words, the production of specific *effects* can be used to produce emotional, *affective* responses. Different effects can be used to affect the perceptions and experience of the forms, surfaces, and spaces; they can embody meanings, evoke feelings (Kolarevic and Klinger, 2008). Affect is the moment when the emotions or imagination of an observer are stimulated by their experiencing of an architectural space. Ideas about material sensations in architecture are nothing new. They were however lost with the ideology of the modernist era which preferred function over sensation. The creation of emotional environments was one of the fundamental concepts driving the Baroque architecture of the 17th century, which employed concepts like "glow" to fuse architecture, sculpture, and painting for architectural affect and religious affirmation. (Erdman, 2009). Marcelo Spina describes material sensations as "formal and material arrangements that could produce distinctive feelings independent from the particularities of the chosen material" and "deal with issues such as surface, articulation, perforation, texture, materiality, and tactility." (Spina and Huljich, 2009) Material sensations interact with the body and aspire to effect the viewer's emotions. Ornament is a fundamental instrument in the production of sensations. Ornament then *does* have a function. It functions to provoke feelings, aides in the creation of certain atmospheres and allows for cultural interventions, among others. Ornament is the figure that emerges from the material substrate, the expression of embedded forces through processes of construction, assembly, and growth. (Moussavi and Kubo, 2006). Kostas Terzidis focuses on addressing the sensate qualities of form, rather than material in his book, *Expressive Form.* He defines expressive form as embodying some of the most intrinsic, existential, and unique qualities of form: *character and identity*, and that it captures the ontological spirit of form and it's shaping forces; it manifests meaning, significance, and quintessence. (Terzidis, 2008).

Academic research

Digital fabrications programs are springing up at a variety of different universities across the nations including, Colombia University, Southern California Institute of Architecture (SCI-ARC), Ball State University, and The Georgia Institute of Technology, among others. I was privileged to have the opportunity to visit the digital fabrications lab at the Georgia Institute of Technology, which I believe was an important and informative visit. Georgia Tech has recently added a post-professional Master of Science in Architecture program that concentrates on parametric modeling and generative design to close the gap between conception and realization. It allows for students to learn advanced scripting and digital modeling tools as well as cutting edge fabrication processes. In Georgia Tech professor, Lars Spuybroek's, book *The Architecture of Variation*, he states that digital design has become "a curriculum in itself, a school within a school", "often resulting in additional graduate and undergraduate programs, post graduate programs and special labs that attract students from all over the world". (Spuybroek, 2009) Their fabrication lab contains numerous advanced production machines including a 5-axis CNC mill and a vacuum former, among many others. As previously mentioned, a primary advantage of a 5-axis mill over a 3-axis mill is that it allows for the production much more complex geometries with greater ease than a 3-axis machine. A facility with more complex production tools could be expected to yield a greater variety of projects with more intricate geometries. The ability to produce a variety of full scale models through digital fabrication projects, both provides inspiration to future students, but also serves as research material. (Spuybroek, 2009).

Material research conducted by Harvard University's Graduate School of Design in 2002 explored what new materials suggest for the future of architecture. Toshiko Mori emphasized the need for architects to regain contact with the material fabrication processes that has been lost as a result of relying on software programs that allow us to solve problems quickly and easily, but are often deceptive in terms of appearance of design completion. (Mori, 2002) Designers need to have a closer relationship with the fabrication process and material research to allow them "to better employ traditional materials" and also "to embrace the possibilities presented by new materials." (Mori, 2002) This study focused on the developing new materials and techniques through built applications focusing of the categories of *edge*, *surface*, *substance*, and *phenomena*. By understanding materials' basic properties, pushing their limits for greater performance, and at the same time being aware of their aesthetic values and psychological effects, an essential design role can be regained and expanded (Mori, 2002).

Currently, PROJECTiONE, a group of graduate students at Ball State University, are investigating the relationships between digital and analog techniques, the tools that exist in software and hardware, and the potentials of these processes to be challenged to create innovative design solutions. They emphasize their position as relying on an intimate understanding of a variety of tools, both analog and digital and then applying this towards the development of innovative relationships. (PROJECTiONE at Ball State University). Simultaneously, the Institute for Digital Fabrication at Ball State, i.M.A.D.E (innovation in manufacturing + design), acts as a catalyst of digital design and fabrication techniques for both industry and education related to architecture and allied arts. They frequently collaborate with industry professionals for to develop solutions to real problems by managing a complex set of design constraints. These types of programs give students the unique opportunity to gain knowledge from actual hands on projects and experimentation. It helps to create a better understanding of the production tools available as well as how different materials behave under different conditions. Building at a 1:1 scale allows for a true understanding of architectural spaces that we are designing, with a higher level of integrity than through digital modeling alone.

CHAPTER IV

FABRICATION TECHNIQUES AND RESULTS

This section is meant to provide the details of the specific fabrication procedures used for our project, *Malbec*, and to present the findings of materials research for different kinds of foams. The overall design of *Malbec* was done by my research advisor, Gabriel Esquivel, and another student, Chris Gassaway. The fabrication of the project was executed by Professor Esquivel, Matthew Richardson, Jeff Quantz, and me. We also used a fabrication consultant from Yale University, Cody Davis to help with the fabrication of the 3-dimensional piece. I will explain the design intentions and present the machine and material limitations that governed much of the fabrication process followed by the techniques used and the overall outcomes. Provided is also an introduction to the different modeling and fabrication software used and the steps that were used to convert between the two.

Design intent

Malbec was designed to be a prototype for a non-transparent digital storefront which uses rustication as its articulation. Its primary intention was not to be representational of an actual façade but rather an engage the scale of the human body in an architectural way and conjure certain emotional, sensational responses through its form, surface articulation and materiality. It was intended to be exhibited in an indoor gallery space for the duration of 3 months so the material needed to be light-weight, while still resilient enough to undergo transportation, and be able to handle a display time of 3 months. It needed to be a pliable material that could be easily sculpted into a smooth organic form. The design was also intended to have a glossy, plastic-like effect, so it had to be able to withstand a paint finish without disintegrating. Because of these design requirements and our method of fabrication being a 3-axis CNC mill, we knew that some type of foam would work the best since both wood and metal would be too heavy and difficult to sculpt. The design consists of an approximately 8’ by 8 ½’ area of wall panels and a 10’ by 3’ completely 3-dimensional “branch” structure. The panels were designed to be flat on one side, where they attach to the wall, while the branch structure is suspended above an opening in the wall and must be hung from above. Figure 1 shows an elevation of the design relative to the scale of a human.

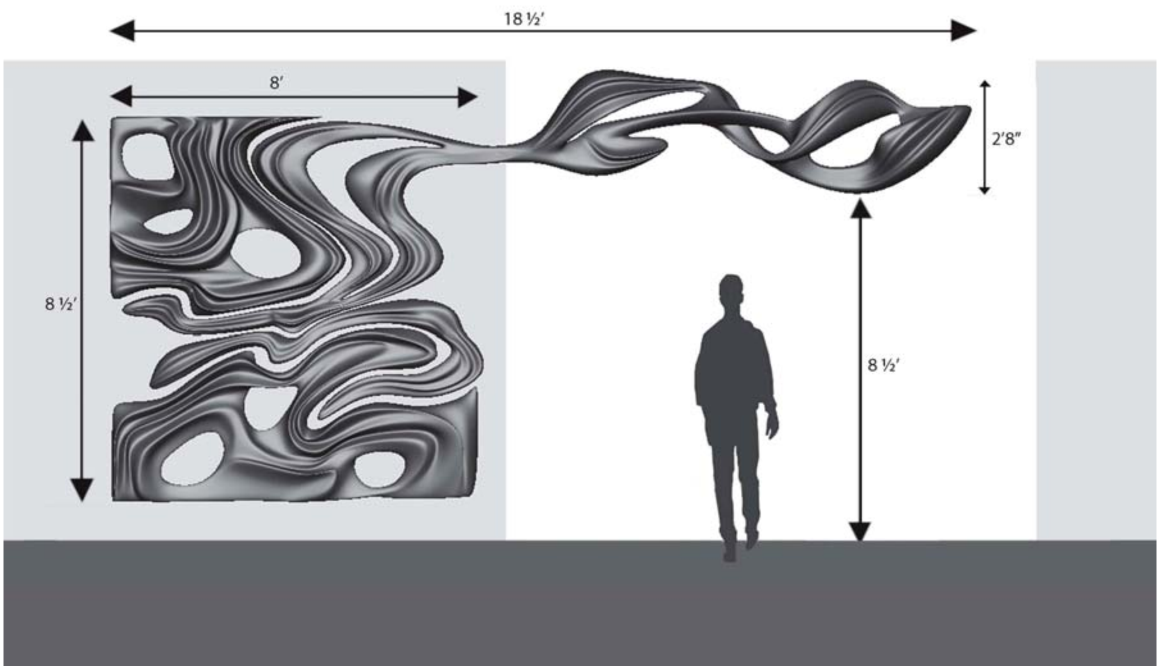

FIGURE 1. Dimensioned elevation of the overall design.

Materials

We first experimented with 1/2” thick, 4’ x 8’ polystyrene insulation foam from Home Depot. This type of foam worked well during test mills, however there were several problems. First, the sheets only came in 1/2” thick sheets, without special order and therefore, 8 sheets had to be laminated together in order to achieve the desired material height of 4 inches. This led to testing of multiple means of adhesion. We experimented with contact-cement, spray adhesive, and finally Elmer’s glue. All of these worked to some degree, but often came unglued, with Elmer’s working the best out of the three. All glues left bands or seams of residue that were difficult to sand away after milling that gave a “striped” effect to the form. Secondly, this type of foam disintegrated when painted directly with certain types of paint. Figures 2 shows the first and second test mills of this type of foam, with the second having a coat of acrylic paint and a spot test of car paint on the end.

FIGURE 2. Poly-styrene test mills. Unfinished, and finished with primer and car paint.

Our next step was to experiment with poly-urethane foam, which is a common foam that has been used for CNC milling. Poly-urethane is more expensive than polystyrene but comes in a variety of different densities, typically in 2 pound increments with the higher the density of the foam, the higher the strength. It also comes in 4’ by 8’ sheets with varying thickness which allowed us to eliminate the step of laminating sheets together. We decided to use primarily 2 pound density foam for the wall panels but 10 pound density for the “neck”, or beginning of the sculpted 3-dimensional piece where we anticipated there would be weakness.

Machine limitations

Using a 3-axis CNC router comes with many strict limitations as far as what can physically be milled, which forced us to think creatively when trying to fabricate pieces that cannot be directly fabricated with this machine, such as the “branch” structure of the design. The wall panels were much more straightforward to mill because of their flat back. The machine was only needed to detail the surface on the top and cut out each panel, whereas we had to devise a technique that allowed us to mill and accurately assemble the branch structure that had curvature on each side. Since we were confined to using a 3-axis mill, we were limited to 3-axes of movement, in the *x* and *y* directions and limited movement in the *z* direction, approximately 4 ½ inches. While 3-axis CNC machines come in a variety of different types, the particular machine that we used had a stationary work-table with a carriage and gantry that move the tool in the *x* and *y* axes above the work, as seen in Figure 3. While this machine type allows for any number of complex geometries to be carved out, it is limited to 3 axes of movement, and does not allow for material to be removed from the sides, or undercuts (Schodek, et al. 2005).

FIGURE 3. Stationary three-axis CNC machine. Sheets of 4’x8’x4” poly-urethane foam on the cutting bed ready to be milled.

Sectioning technique

Before we could actually begin the fabrication process, we had to decide how the model was going to be broken up, and the location of joints since the overall design is much larger than a single sheet of foam which is 8’x4’x4”. The wall panels were designed so that they could each fit within a sheet of foam with only one of the pieces having to be split in two pieces. The branch structure of the design that extends to the right of the paneled wall pieces was designed to be completely 3-dimensional, a total sculpture with curvature on each side and perforations. Since a 3-axis mill does not have the ability to make undercuts, our biggest challenge was to figure out a technique that allowed us to fabricate this piece. A sectioning technique was used to split the piece into separate horizontal sections since the overall length was longer than 8 feet. It was then further sectioned vertically with each sectioned piece not extending higher than 4 inches, due to the height of the foam stock. With this technique, we were able to mill many small pieces of the overall form that fit together much like a giant jigsaw puzzle. The red lines in Figure 4 show where the form was cut in both elevation view and plan view. Undercuts were not completely unavoidable but we tried to avoid them as much as possible, and the parts where undercuts could not be avoided had to be sanded by hand to approximate the geometry. Figure 5 shows an exploded axonometric of the overall branch structures and the separate pieces that make up the whole. By organizing the horizontal sections alpha-numerically, we were able to assemble the pieces of each section separately before combining the separate sections.

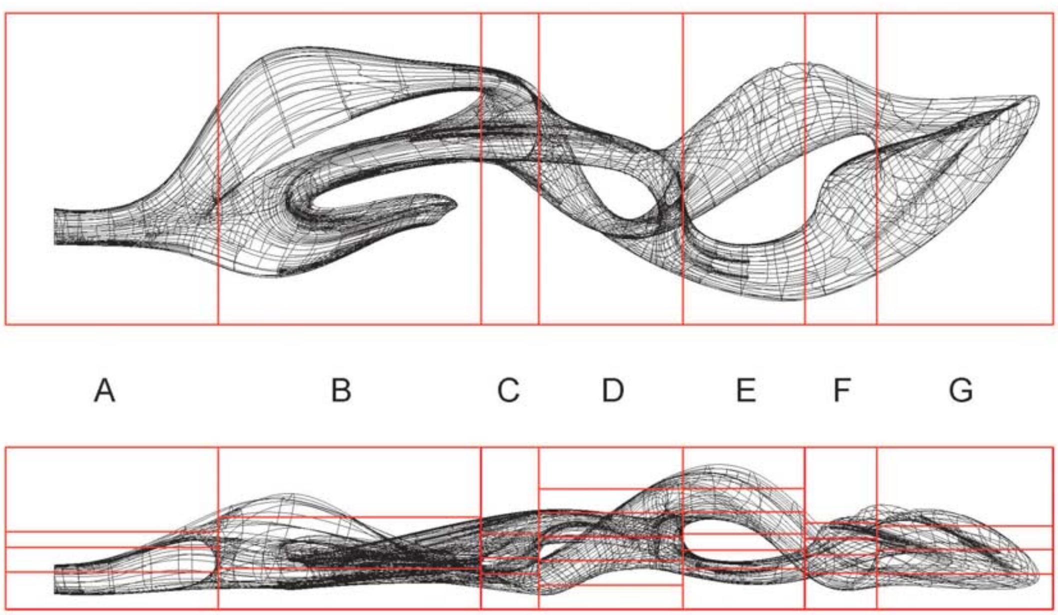

FIGURE 4. Elevation and plan view of branch structure. Red lines indicate cuts in the form to allow for fabrication.

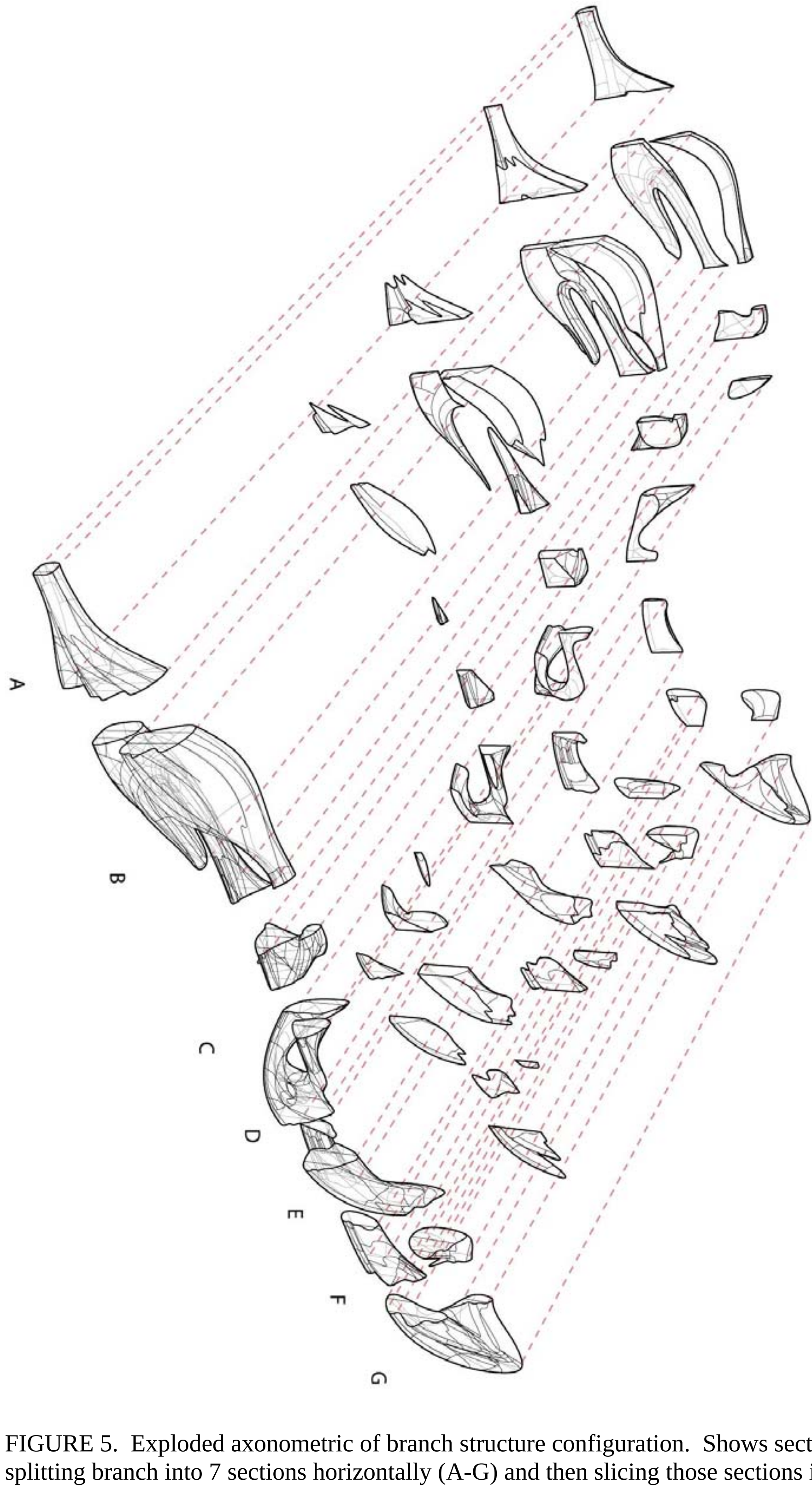

FIGURE 5. Exploded axonometric of branch structure configuration. Shows sectioning technique of splitting branch into 7 sections horizontally (A-G) and then slicing those sections into 4 inch high pieces.

Modeling conversion and pre-milling preparations

The form was modeled in Autodesk Maya using polygonal modeling. Polygon surfaces in Maya are a network of 3-or-more sided flat surfaces that are connected together to create a "poly-mesh". In order for the file to be compatible with the manufacturing software that controls the CNC machine, MasterCAM, it must be a Rhinoceros file and a NURBS surface. NURBS (Non-Uniform Rational B-Splines) use a method of mathematically describing curves and surfaces that are well suited to 3D applications. NURBS are characterized by the smooth organic forms they produce. After the polygonal surface was converted to a NURBS surface in Maya, we exported the file as an IGES (Initial Graphics Exchange Specification) format and then imported it into Rhinoceros to set-up the individual surfaces to be milled.

Cut-file set-up

Since we knew the size of our material stock, we drew a 4' x 8' plane in Rhino and placed the form to be milled in the center of the plane. This ensured that the edges of the form would not be slightly cut off due to inevitable inaccuracies when we aligned the foam on the cutting bed of the machine. We also had to make sure that the modeled form did not extend below the plane in the *z* direction, as the machine would read that and try to cut below the bottom of the material into the bed of the table. The trim command in Rhino was used to trim off the model that was below the level of the plane. We then imported each "cut-file" in MasterCAM, which converted the data from the digital model into a language that the CNC mill could understand and accurately produce. Figure 6 shows the actual cut-files that were used to in MasterCAM to fabricate the entire design.

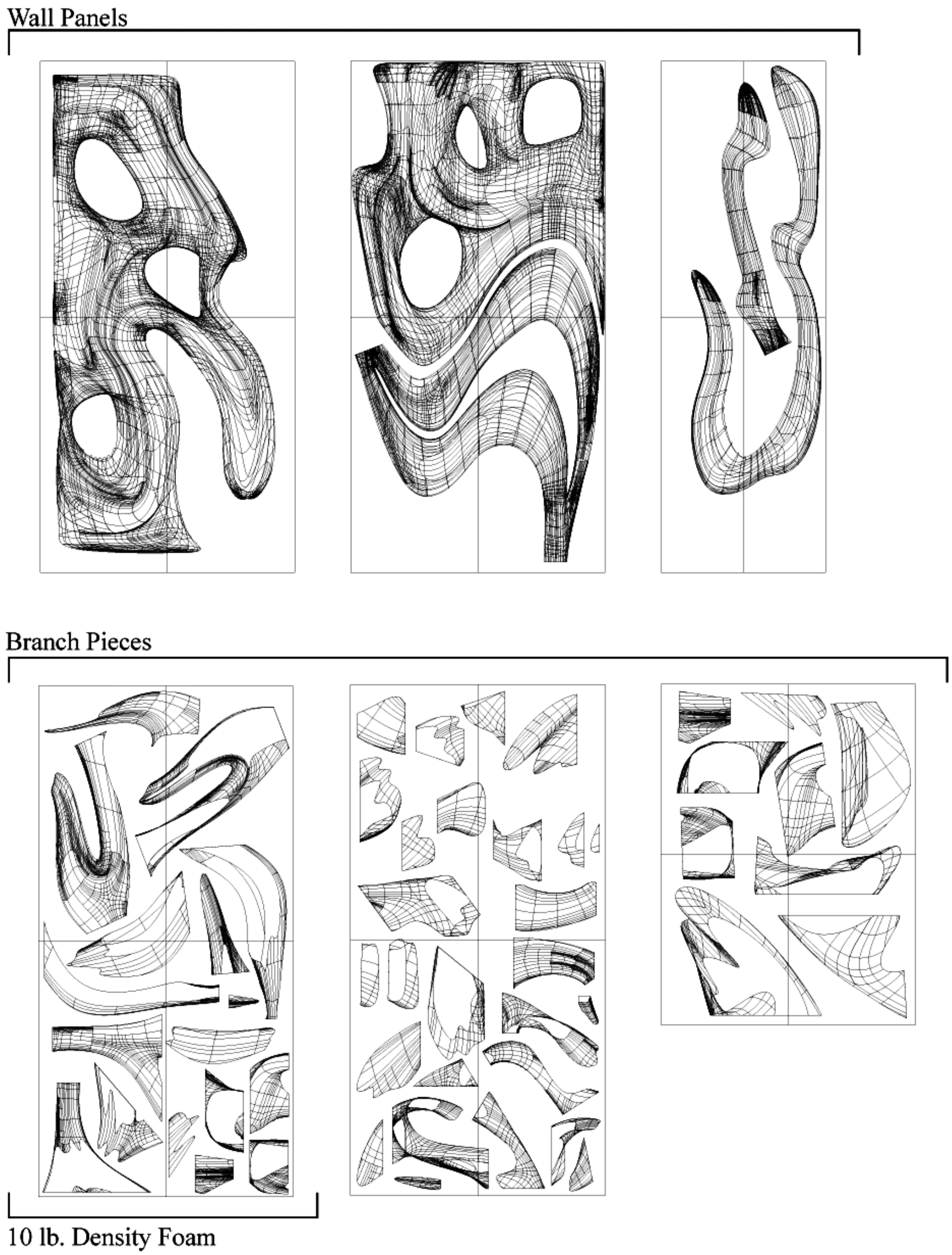

FIGURE 6. Cut-files. These were the files used in MasterCAM to fabricate wall panels and branch pieces in 4 ft. by 8 ft. by 4 in. sheets of poly-urethane foam. All sheets were of 2 lb. density except where indicated otherwise.

Material set-up

Before we could begin milling we had to set up the actual material stock (4’x8’x4” foam) on the cutting table, put in the specified bit, and then actually tell the machine where 0, 0, 0 is by “touching down” the bit. We always made sure there was a smooth composite board or masonite, i.e. “sacrifice board” so that the bit would not be ruined if it for some reason went below our material stock. Because the foam we used is extremely light-weight (2 pound density) we had to figure a way to keep the foam from moving during the milling process. We first tried double-sided foam tape, which was semi-strong but we still had problems with the foam coming un-stuck. It also has about a 1/8” thickness, which allowed for dust to get underneath the material and loosen the tape. Next, we tired double-sided carpet tape which was stronger and worked the best. We laid down strips of the tape length-wise on the composite board with 3 inch to 4 inch spacing between the strips and placed the foam on top. We also drilled scrap polystyrene “holders” around the perimeter of the foam to also help keep the foam from moving as you can see in Figure 1.

Milling

Depending on the size of the form to be milled, the actual milling process usually took about 3-4 hours for the rough-cut and about 2 or more hours for the finish-cut. We had to always have someone monitoring the milling, ready to stop the machine if a problem occurred. It was extremely important that the foam not move during the rough-cut because if it moved, it was impossible to re-secure the foam in the exact same position, and resulted in an inaccurate finish-cut. Rough-cut is the term used to describe the first round of cutting that essentially gets the rough overall form cut out from the block of foam; the machine typically has ½” to 1” step-downs during the rough cut. The finish-cut is where the machine goes back and refines the surface of the form with much smaller step-downs and results in the smooth finished form, as seen in Figure 7. Figures 8-13 show the milling sequence of the rough and finish cuts. Milling was a very time consuming process, in which the machine does all or most of the work. Those who were not monitoring the machine used this time to assemble and finish the milled pieces that had already finished.

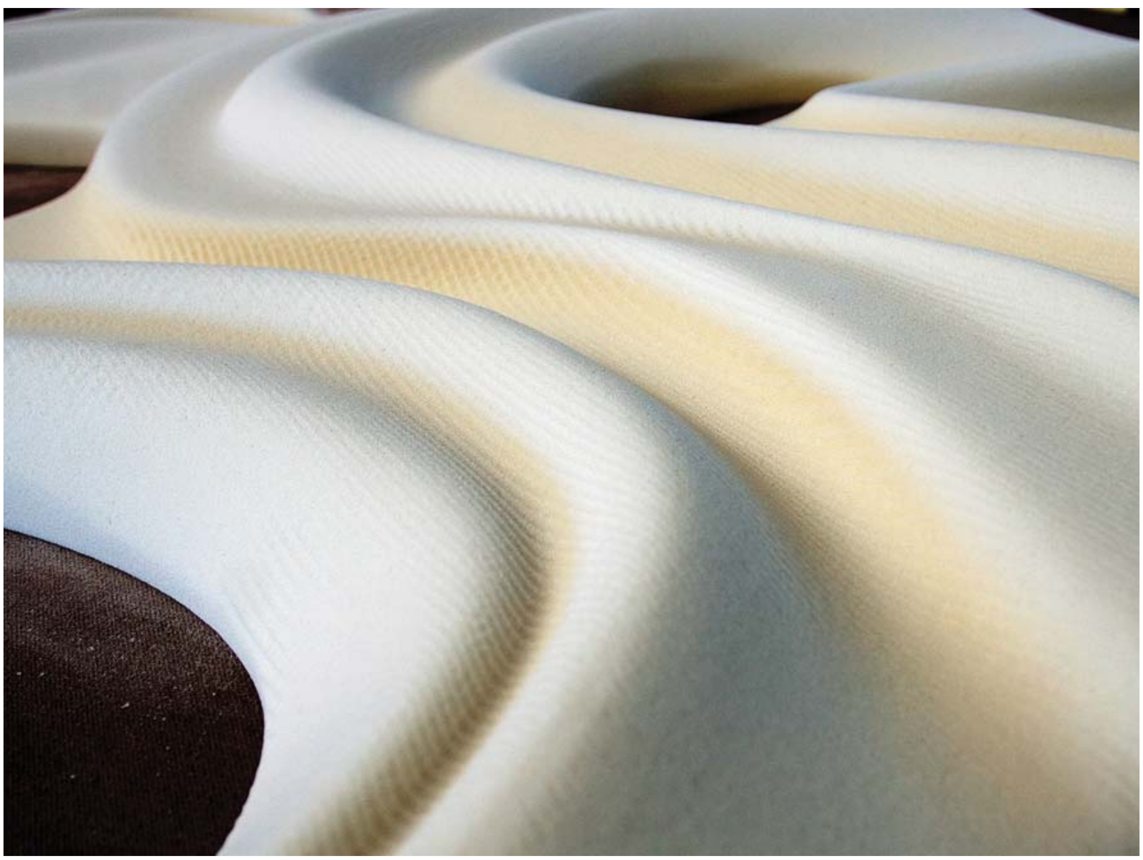

FIGURE 7. Detail of milled surface. Taken after the finish-cut and before sanding and finishing.

FIGURE 8. Rough cut first step down.

FIGURE 9. Rough cut second step down.

FIGURE 10. Rough cut third step down.

FIGURE 11. Rough cut forth, final step down.

FIGURE 12. Close-up of rough cut surface.

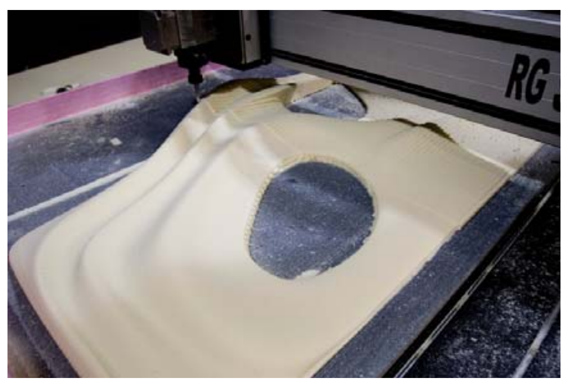

FIGURE 13. Finish cut.

Finishing

The finishing process began as soon as each piece was done milling and another was started. For the large panels, finishing was much more simple than for the sculpted 3-dimensional pieces that had to be joined together first. The finishing process consisted of sanding, lacquering, application of joint compound, more sanding, assembling and finally painting. One of the most important steps was to have a system of organization for the 3- dimensional pieces so that we could know which pieces went together and how they fit.

Organization

For the 3-dimensional sculpted pieces, there was a good deal of coordination back and forth between the computer model and the milling table for the arrangement of the pieces. The sculpted piece that was sectioned in Rhino was labeled A, B, C, D, E, F, and G, according to the corresponding horizontal segments. Then each segmented portion, sectioned in 4 inch increments, was laid out on the milling stock and labeled according to which section they belonged to (A-G). When the milling of these panels was finished, the pieces were taken directly off the cutting table and grouped on tables according to their appropriate groups, denoted by pieces of tape identifying the lettered groups, as seen in Figure 14. The appropriate configurations of the pieces within the groups were determined by examining the computer model. We found that it was much easier to figure out the configurations directly from rotating the computer model than it would have been with paper construction documents. The pieces where undercuts could not be avoided, were sometimes more difficult to identify since they came out looking quite different than in the digital model.

FIGURE 14. Organization of milled branch pieces. Arranged according to their appropriate section (A, B, C, D, E, F, and G).

Sanding

After pieces were organized, all parts of the milled wall panels and pieces were very lightly sanded, to smooth out the ripples from the finish cut. We used very fine grain sand paper, typically 180 grit or higher. For the sculptural 3-dimensional pieces, to achieve the smoothest forms, it was best to glue the pieces together before sanding, so that the joints would remain flush.

Application of lacquer and joint compound

The 2 pound density foam that we used for the majority of the form was incredibly soft and could be easily dented or nicked simply by touching it. We realized that in order for this foam to sustain transportation and installation in a gallery we had to devise a way to strengthen the material so that it would not be so easily blemished. We found that a simple application of traditional wood lacquer added a good deal of strength to the material. As it dries, it hardens the foam and gives it a much stronger surface that is not as easily nicked. It was important to be sure that there would be no more sanding or changes to the basic form of each piece after this application, because it was very difficult to do after the lacquer has been applied. After the lacquer was completely dry, we applied a thick coat of joint compound, typically used for dry-wall, to the surface, as seen in Figure 15. Using rubber kitchen spatulas, we were able to easily smooth and sculpt the form. The application of joint compound allowed for holes and blemished to be filled that might have happened during milling or sanding. After the initial coat of joint compound dried, we lightly sanded the surface again to smooth out the lumps, and then repeated the process with a final coat of joint compound and one more round of light sanding. This was to ensure the surface was as smooth and fluid as possible, and that it was thick and durable enough to withstand automotive paint.

FIGURE 15. Wall panel before and after joint compound.

Assembly

The method that was outlined above was used for the majority of the form, including the wall panels, but a slightly altered method was used for the sectioned pieces that had to be assembled together as well. For these pieces, we first glued the pieces together according to their segmented categories (labeled A through G) using an epoxy resin and hardener. After the glued pieces had dried, we sanded the complete forms to achieve a more uniform smoothness, and even out the joints, as seen in Figure 16. The lacquer, joint compound, sanding method was then used on each entire assembled form. After each assembled form was dry we began to piece together the separate segmented groups. Since the entire length of the branch was over 8 feet long, we decided to join all of the pieces into two separate branches rather than one large one to allow for easier transportation, and installation. Because this sculptural piece would be suspended over an opening by wires, the connections needed to be very strong so that the branch would not break at the weak joints. For the weaker joints, especially those where the 10 pound density foam had to be joined to the 2 pound foam, we used metal dowel rods to hold the pieces together, as seen in Figure 17. We first drilled holes through the two separate pieces and inserted the metal rods, coated in epoxy resin and hardener, into them at opposing angles to add strength and stability. In some cases, such as joining pieces that were both 2 pound density, we used shorter wooden dowels instead. When using the dowel rod method of connecting the pieces, we always made sure to coat the face of the connecting surfaces in glue to ensure a tight joint. After the pieces were joined, we applied generous coats of joint compound to smooth out and hide the seams. This often had to be repeated several times to achieve the smoothest seams.

FIGURE 16. Assembled section of branch. Unfinished.

FIGURE 17. Joining of branch structure sections. With the 10 pound density foam, metal dowel rods were used and with the 2 pound density foam wooden dowels were used.

Painting

The painting of the wall panels and branch structure was done by a professional automotive paint shop. This was the final finishing technique used and was successful in giving the foam the glossy effect as seen in the close-up of the surface in Figure 18. Overall, the joint compound was a sufficient base for the automotive paint finish, although it tended to absorb the paint in certain areas which resulted in a less glossy finish it some parts. We predict that using automotive grade putty such as Bondo would help to solve this problem. Figure 19 shows the final digitally fabricated design installed in the gallery space.

FIGURE 18. Finished wall panel detail. Finished with automotive paint.

FIGURE 19. Final gallery installation.

CHAPTER V

SUMMARY AND CONCLUSIONS

One might have a moment of hesitation in beginning a project like this as to whether or not it is a valid research endeavor. However, after the completion of this project I have come to the conclusion that it is precisely these kinds of research projects that are absolutely necessary undertakings in an area of design that is so far ungoverned by rules and industry standards. The relationship between design and production is in a period of transformation and flux, and it is up to projects like *Malbec* to help re-conceptualize this relationship, pushing the boundaries of what is possible. This project has demonstrated that our means of design conceptualization, and material realization are no longer fixed entities. Through an understanding of our available production tools and through material experimentation, these traditional roles can be expanded and innovation can occur. Although we were confined to a 3-axis machine with only 4 inches of milling height, we found a way around this problem to produce completely three-dimensional form, greatly exceeding the 4 inch limitation. Moreover, the material affects achieved through compounds and finishes gave the finished product the ability to completely remove itself from any original material recognition. *Malbec* achieves plasticity, and a liquid, dynamic materiality that makes the original poly-urethane foam unrecognizable.

It is my hope that this project that this project will help to generate interest and enthusiasm for digital fabrication at Texas A&M and that it will encourage more students and professor to conducted research projects in this area. I believe that as students are beginning to have the opportunity to build at a 1 to 1 scale, the amount of knowledge gained from this experience will help to prepare them for work in the professional field. It is my hope that the documentation and analysis part will help to create a better understanding of where the possibilities lie in terms of the process. As of now, projects move in a linear fashion from software to hardware to finally analog, but I believe that this process can be challenged and better integrated to create a more collaborative exchange of information on all levels from design to production.

Limitations

This project is limited in terms of generality, since each fabrication is project-specific and most likely cannot be applied to a broad range of design problems. It does however maintain a higher degree of reliability especially because the documentation is compiled as step-by-step narrative. Anyone that follows these exact steps should be able to achieve the same results, therefore verifying that what I have provided is reliable. The availability of a CNC mill with a greater number of axes of rotation would allow for a much faster fabrication time and could have greatly simplified our assembly process, as well as cutting down on material waste. We believe that it was important to not allow the restrictions of the machine to limit the complexity of the design. Instead, we focused on finding innovative solutions that allowed us to deal with these limitations in a creative way and not sacrifice the integrity of the design. I believe that this was legitimate research project because “each new experiment and each new collaborative pursuit will help broker change as projects move towards redefining techniques and methods of design conception and material realization.” (Kolarevic, Klinger, 2008). Each new project is unique and will add to the collective body of knowledge concerning this relatively new and rapidly expanding field of design.

REFERENCES

Eisenman, P. (1992). Affects of Singularity. *Architectural Design*, 62, 42-45.

Erdman, David. (2009). "Glow(ing)." *Log 17*. [S.l.]: Anyonrrp. 49-51. Print.

Iwamoto, L. (2009). *Digital Fabrications Architectural and Material Techniques*. New York: Princeton Architectural P.

Kolarevic, B., & Klinger, K. R. (2008). Manufacturing/Material/Effects. In, *Manufacturing Material Effects Rethinking Design and Making in Architecture* (pp. 5-24). New York: Routledge.

Mitchell, W. J. (2008). [Foreword]. In *Expressive Form: A Conceptual Approach to Computational Design* (pp. vii-viii). New York: Spon Press.

Mori, T. (Ed.). (2002). *Immaterial/Ultramaterial Architecture, Design, and Materials*. Cambridge, Mass: Harvard Design School in association with George Braziller.

Moussavi, F., & Kubo, M. (2006). *The Function of Ornament*. Barcelona: Actar.

Reffat, R. M. (2008). Digital Architecture and Reforming the Built Environment. *Journal of Architectural and Planning Research*, 25 (2), 118-129.

Schodek, D., Bechthold, M., Griggs, K., Martin Kao, K., & Steinberg, M. (2005). *Digital Design and Manufacturing CAD/CAM Applications in Architecture and Design*. Hoboken, NJ: John Wiley & Sons.

Speaks, M. (2002, January). Design Intelligence and the New Economy. *Architectural Record*, 72-76.

Spina, Marcelo, and Georgina Huljich. (2009). "Ouch or Ooooh? On "Matters of Sensation"" Ed. Todd Gannon. *Log 17*. [S.l.]: Anyonr Corp. 93-104. Print.

Spuybroek, Lars. (2009). *Research & Design: The Architecture of Variation*. New York: Thames & Hudson. Print.

Steele, B. (2008). Prototyping Architecture's Future, Again [Foreword]. In *Manufacturing/Material/Effects* (pp. 1-4). New York, NY: Routledge.

Terzidis, K. (2008). *Expressive Form: A Conceptual Approach to Computational Design*. New York: Spon Press.

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