From Bézier to NURBS: Integrating Material and Digital Techniques through a Plywood Shell

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Abstract

The development of digital fabrication has reintroduced material processes with digital processes. There has been much discussion about the tool and the objects of the tool, but little discussion of the implication of the material process on the digital process. A brief historical review on the development of computer numerical control and the origins of the Bézier curve reveals an instrumental fact: computer numerical controlled tools necessitated advancements in computational surfaces which eventually led to NURBS (Non-Uniform Rational B-Splines) surfaces. In other words, the origins of NURBS surfaces resides in its relation to material processes, rather than many current approaches that develop free form surfaces and then force the tool onto the material without regard to the material properties.

From this historical and mathematical review, this project develops toward more intelligent construction methods based on the integration of NURBS differential geometry paired with material qualities and processes. Specifically, a digital technique of developing conceptual NURBS geometry into piecewise surface patches are then flattened based on the material thickness and density. From these flattened patches, a material technique is developed to intelligently remove material to allow the rigid flat material to re-develop into physical surface patches. The goal of this research is to develop digital and material techniques toward intelligent construction based on the correspondence between digitally driven surface and digitally driven material processes. The application of this technique as a rational and flexible system is to support the dynamic response of form and material toward such performative aspects as structure, daylight, ventilation, and thermal properties.

“Each idea must be related to the principle of a material system, simple and primitive though it may look, on which a variable solution could be based.”

Gerald Farin, Curves and Surfaces for Computer Aided Geometric Design
Introduction

The recent focus of digital fabrication in architecture has reintroduced material processes with digital processes. Since at least the early nineties, the accessibility of both computer software and hardware motivated a formal renaissance in architecture propelled by glossy renderings. This formal emphasis has only been compounded with the ease of formal manipulation enabled by non-uniform rational b-splines (NURBS). With the recent introduction of computer numerical control (CNC) in architecture, the ability to build this formal manipulation is no longer novel. Moreover, the approach to formal development and material fabrication is met with a certain schizophrenia: formal development up to a point, and then the form is handed over to be sliced up, often in orthographic sections, to then be milled. Although NURBS were introduced to architecture before CNC technologies, the origins of NURBS are tied directly to a material system. This research project was motivated by the fact that Pierre Bézier, arguably the forefather of NURBS, wrote a book on numerical control nearly ten years before publishing his slightly more well known book on the Unisurf CAD System. (Bézier) Further reading reveals a startling fact: Bézier and others at the time developed the foundation of what is now NURBS as a result of the development of computer numerical control in the 1960’s. The irony is that early CNC technologies inspired the foundation for NURBS - not the other way around. In other words, the tool necessitated more robust techniques to exploit the tool. While CNC technology gives the possibility to slice up any shape and fabricate it, is there not a more robust approach to integrating form and material through the relation between NURBS and computer numerical control?

The motivation behind this question is two-fold. First it is presumed, and all too frequently the case, that the software leads the development of form through its encoded emphasis with the designer’s direction and intentions filtered through that medium. For example, in one case study “Form Follows Software,” it is argued that each software interface either enhances or hinders the development or 3-d alternatives beyond the default primitives. (Serriano 187) Furthermore, it is argued that the formal flexibility of NURBS-based programs, which is more akin to digital clay, is an accomplice in obscuring the tectonics of these artifacts. (Serriano188-9) Although there is no doubt evidence to support these two theses, is this necessarily so? First, even if one only conceptually understands the mathematical principles behind NURBS, learning the software is a question of preferable interface, not of encoded bias or proprietary tricks. Secondly, understanding the origins of the material processes that inspired NURBS development implies an obvious link to material systems and processes, bringing into the digital process a question of material making. The argument presented here is that there is a great deal more information embedded within the NURBS surface than merely representing a shape, but indeed in directly fabricating it.

Briefly three built examples are given which form the parameters of this particular research project. Then, a brief overview of b-spline principles are introduced that lead to both a working vocabulary and certain techniques that are a more materially informed approach to working with NURBS. Specifically, a digital technique of developing conceptual NURBS geometry into piecewise surface patches are then flattened based on the material thickness and density. From these flattened patches, a material technique is developed to intelligently remove material to allow the rigid flat material to re-develop into compound curved surface patches. This technique is demonstrated through a rigorous and replicable computational process, and fabricated as a full-size installation. The goal of this research is to develop a technique toward intelligent construction based on the correspondence between digitally driven surface and digitally driven material processes. The application of this technique as a rational and flexible system is to support the dynamic response of form and material toward such performative aspects as structure, daylight, ventilation, and thermal properties.

Precedent

Examples of digitally fabricated structures are now ubiquitous, at least in the architectural media. Despite their formal eloquence, these projects generally rely on similar techniques of description and development to fabricate these forms. The evolution of materially informed processes on digital development occurs at a much slower
timeframe than the speed of which formal representation can be published through images and publications. For example, a close inspection of Frank Gehry’s work from the Guggenheim in Bilbao, to the Experience Music Project in Seattle, to the Sosnoff Theater at Bard College, and the Disney Concert Hall in Los Angeles reveals a slow but significant impact of material processes and digital development revealed in the actual experience of the work through smaller details that are often glossed over in publications. Although the Disney Concert Hall technically predates the Guggenheim project, the long delay and consequent redesign and redevelopment of the Disney Concert Hall reveals the development and knowledge based experience of both Frank Gehry’s office and the fabricators that his office works with, with the most obvious example, among many, being the move from a curved limestone skin to a titanium skin. Three more succinct examples that illustrate an evolution of technique are Bernard Franken’s BMW pavilions “The Bubble,” “The Wave,” and “The Brandscape” developed between 1999-2000. These pavilions are simple programmatically and illustrate an explicit focus on developing material/digital processes through these projects.\(^2\)

The Bubble’s main structure was developed through orthogonal slicing yielding a rigid egg-crate representation of the form. The precise form is then enclosed with acrylic sheets thermoformed from CNC milled polyurethane molds. Despite the egg-crate structure, the pavilion’s novelty resides in its use of compound curved surface patches as opposed to geometrically reduced ruled surfaces.\(^3\) While these acrylic patches directly correspond to the digital model, they are clearly not structural.

The following year, Franken’s pavilion “The Wave” and similarly developed “Brandscape” focused on evolving the primary structure away from the egg-crate approach. Instead of representing the form through the approximation of orthogonal slicing, the evolution in these projects is using the iso-parametric information embedded into the digital model to develop the doubly curved steel pipe structure. However, the CNC pipe-bending machine only curved pipe in one direction, and therefore the doubly curved structural section was segmented into approximately 100 singly curved pieces. The secondary structure similarly consisted of a lattice of double curved aluminum tubes, but due to the flexibility of the aluminum section, and the gentler degree of curvature in one direction, each aluminum lattice line could be CNC bent in one direction and curved into the second direction as they are fixed in place. The skin in this pavilion is simply fabric stretched between the lattice openings.
Although these projects are now five years old, the evolution these projects present appears to have met an impasse, as there has been little further development in this direction. Specifically, despite the Bubble’s egg-crate structure, the thermoformed surface patches are developed from a direct translation of the digital form to material form, albeit with the less than desirable intermediary mold. In the Wave, the primary structure develops directly from the iso-parametric information embedded in the surface. The limitation of this project is the compounded cost in assembly of the singly curved steel segments to build the doubly curved iso-parametric lines of structure, yet an opportunity is also revealed through the natural characteristic of certain materials to bend in at least one direction, such as the aluminum tubes. Combining the assets of both of these projects, is there not a way to combine the embedded information of the iso-parametric lines with a structurally rigid surface patch to develop a true free-form self-supporting structurally rigid shell?

From Bézier to NURBS: Principles of B-Spline Differential Geometry

It is not the intention of this historical review to follow the derivations of the differential calculus of these mathematical curves, but to uncover the implications of this mathematical basis on material form. It cannot be overstated that these advanced mathematical techniques were motivated by the burgeoning methods of computer numerical control in the automotive industries at Citroen and Renault in Paris, and Ford and GM in Detroit. (Farin 363)

Through the understanding of a couple principles behind b-spline geometry, a more intelligent correspondence between digital and material process is possible. Of principle concern here is first the idea of piecewise construction exemplified through the evolution of the Bézier curve into the b-spline. Second, exemplified through the development of Coons surfaces, which is mathematically speaking a patch, outlines the differences, and potential, of distinguishing between a patch and a surface. The combination of these two principles leads to a materially informed technique of rebuilding conceptual NURBS surfaces into piecewise bi-cubic patches.

Although many mathematicians were working on the same problem, the French mathematician Pierre Bézier was the first to publish the mathematical basis of what is now known as the Bézier curve. (Farin XV) Generally speaking, the Bézier curve is the basic building block of b-splines and NURBS surfaces. A Bézier curve is comprised of a series of control points, wherein the curve only passes through the first and last control points, or end points. The lines that connect these control points are known as the control polygon. Despite their free form, these curves are the graphical expression of the parametric equation: \[ C(u)= \sum_{i=0}^{n} N_{i,p}(u)P_i \], wherein \( \{P_i\} \) are the control points, and the \( \{N_{i,p}(u)\} \) represents the \( p \)th degree of the Bézier curve. (Piegl 81) In the simple Bézier form, the degree of the curve follows the number of line segments in the control polygon, or one less than the number of control points. For example, the illustration shows a cubic Bézier curve (3rd degree), which is the most

![Figure 4. Cubic Bézier Curve and B-Spline Curve as Piecewise Cubic Bézier Curves](image-url)
common type in computer graphic applications. Alternatively, a Bézier curve of degree one (linear) is a line segment despite being derived from the same parametric expression above. A b-spline, however, can be described as a piecewise construction of Bézier curves where the intermediary control points with the line passing through them are defined as knots.

From these simple elements, a surface can be generated by continuously moving either Bézier or b-spline curves through space, connecting similar curves in the opposing direction to the control points of the generating curve, indicated as \( u \) and \( v \) directions. Mathematically speaking, this is known as the tensor product approach. (Farin 271) In lieu of modifying a given curve over time, a given surface can be modified through its control net, or lattice. These types of surface manipulation are so familiar to architects working with NURBS that their mathematical origins are typically unknown. It is not the particular math that is significant but the rationality in building up the system that is fundamental. Where the b-spline curve is a piecewise construction of Bézier curves with the knot marking the beginning/endpoint of subsequent piecewise Bézier curves, these knots become iso-parametric lines in the surface. Note that a true Bézier surface would therefore have no intermediary iso-parametric lines, which is defined as a patch. Whereas the Bézier curve was seen as the mathematical building block of the b-spline, the Coons patch can be seen as the mathematical basis of b-spline surfaces. (Farin XV)

The mathematician S. Coons\(^4\) is attributed for his derivation of a surface from four boundary curves. Most architects are familiar with lofting, forming a surface from a series of curves or line segments. Lofting between only two curves results in a linear interpolation between them or a surface generated by straight lines or rulings, known as a ruled surface. Coons developed his method of a surface defined by four boundary curves through a technique of bi-linear blending. Each opposing set of curves are lofted with the resultant grid blended into a continuous surface. While the solution of bi-lineal blending this ruled mesh is elegant, it is also problematic as a result of the linear interpolation from one curve to the next. For variable surfaces which rely on more than four boundary curves, as most do, the Coons patch is not informed by neighboring patches thereby creating creases at the boundary conditions. Mathematically speaking, “cross boundary tangents along one boundary depend on data not pertaining to that boundary.”(Farin 369) Although there are blending functions to smooth out these differences, they are frequently undesirable as they alter the defining boundary curves.

This brief knowledge of Coons patches is useful for two reasons. First, although patches may not be as advantageous in conceiving form, there primary benefit is to rationally reconstruct a surface from a given network of curves maintaining the logic of that network. Secondly, with the knowledge that these patches are bended from two ruled surfaces, it is possible to degree reduce these patches in one direction resulting back into a ruled surface.

**Digital Technique: Conceptual NURBS Geometry into Piecewise Bi-Cubic Patches**

While the subject of this paper is not formal conception, it does imply the introduction of material systems and processes at much earlier...
stages of formal development. To this end, the technique presented here relies on simple conceptual geometry, yet the ease of which these two can be integrated suggests an increase in integration between form and material at the earliest stages of formal development. The very limitation of the patch, that “cross boundary tangents along one boundary depend on data not pertaining to that boundary,” becomes the opportunity for this technique of rebuilding the conceptual NURBS surfaces into piecewise bicubic patches. If developed from an appropriately formed network of NURBS, the boundary curves of the patch can be developed as a seam between adjacent patches where the patch boundary edges separated by that seam do share the same tangent. The result is the same continuous curvature of the conceptual NURBS surface but separated as patches.

More significantly, the piecewise construction is not merely a different representation of the same NURBS surface, but the spacing between the isoparametric b-splines (isoparms) can be correlated to the particular material unit sizes. In this example, the conceptual NURBS geometry was rebuilt based on a standard 4x8 sheet size of plywood. These dimensions can be verified through flattening a particular patch (see below) or simply verifying the appropriate spline length.

In conceptual development, a minimum of isoparametric lines will likely be desired to maintain global control. However, once the form is set, it is suggested here that adjusting iso-parametric line density is directly related to product scale and detail when the surface is connected to a material process. For example, the isoparm density would be different for say a stapler, than for a building. It should be made clear that for representational purposes this is nearly irrelevant. However, when tied to material parameters and processes these isoparms exhibit a potential much greater than simply representation. The isoparms can be seen as seams in a material process whereby adjusting the isoparm density creates a correlation with a material dimension and/or a material process. In this way, the process of slicing is not necessary, as the object or building can be broken apart at the seams. For example, in an injection-molded product, I might choose to split the surface more or less down the center into two equal surfaces. However, for much larger products, such as architecture composed of many large pieces, distinct techniques are necessary.

After the given conceptual NURBS surface is rebuilt based precisely on particular material parameters, the surface curves can be extracted and reconstructed as bi-cubic patches in piecewise form. These are termed “bi-cubic” as the b-spline curves in opposing direction are both of cubic degree. Although this is a basic and straightforward approach, when NURBS are only seen as digital representations of form the material implications of this technique would not be apparent. Furthermore, other approaches such as triangulation have dealt with the rough approximation of continuous curvature, but are developed from the reconstruction of the entire surface, globally as a mesh, thus dropping the parametric expression of the generating curves. Triangulation also yields a field of complex joint angles that must be dealt with. By rationally
constructing NURBS geometry, continuous curvature can be achieved while simultaneously simplifying the assembly of joints as a result of their shared tangents, and creating a digital/material synthesis through the correlation of material parameters and process through defined iso-parametric seams. What was the specific iso-parametric line of the NURBS surface, becomes the defining edge of the patch.

Figure 8. Piecewise Bi-Cubic Patches

While the technique of piecewise bi-cubic patches simplifies the joint, the challenge resides in economically fabricating these bi-cubic (compound curve) patches. Of course these surfaces could be milled from a solid chunk of material, though this is obviously time and material consuming. Similar to the acrylic patches in Franken’s Bubble, intermediary molds could be milled and thin sheets of material could be laminated to the mold. However, the most economically and materially desirable solution is to flatten these patches utilizing flat stock material and basic two and three axis CNC technology as these are the most common in the industry. (Kolarevich 34)

At this point in the process, there are two options in flattening the patches to work with flat stock material. The first option is to degree reduce the patch in one direction into a developable surface, and the second option is to use specific software that can flatten compound curve material based on the material thickness and density. A developable surface is a sub-set of ruled surfaces whose rulings are parallel (a cylinder) or concentric (a conic section). As a result, developable surfaces can be iso-metrically mapped, or unrolled onto a plane. A compound curve is simply a curve in both directions, or doubly curved, as in the bi-cubic patches. Although both options require specific software solutions, option one rebuilds the surface into a developable surface such that it can be unrolled regardless of material properties. The challenge of flattening compound curve material is that the material is actually stretching, creasing, and/or tearing and therefore the density and thickness of the particular material must be taken into consideration by the software.

Option One: Degree Reduction of Bi-Cubic Patches to Developable Surface

Although ultimately this project proceeds with the second option, this option results from the review of the mathematical principles of NURBS and will likely be invaluable in different applications. While by definition, the bi-cubic patches (curved in both directions) are not developable; a degree reduction in one direction will yield a ruled surface, or technically a dual degree patch (cubic in one direction and linear in the other direction).

Furthermore, as a result of the piecewise construction of bi-cubic patches, each boundary curve shares the same tangent with the adjacent patch, and therefore through reducing the degree in one direction this technique will yield a developable surface. Pause must be given here to stress that degree reduction in one direction of any NURBS surface will not necessarily yield a developable surface, but will yield a ruled surface. However, in this technique, as the conceptual NURBS geometry is rebuilt through a piecewise construction of patches, this approach to degree reduction should yield a developable surface at each patch.

Although it would be easy to proceed with this project in developable surfaces by unrolling them through Rhino, this formal approximation is not satisfactory compared to the intended compound curve model. Care needs to be taken in which direction to reduce in degree as it not only will effect the appearance of the surface, but depending on the geometry can also split the seams. Furthermore, projects which successfully use ruled surfaces approach ruled surfaces at the conceptual stage of design as a material/geometric restraint, such as the physical paper strips in Frank Gehry’s design process, and not as an approximation of a desired compound curve surface. (Killian 78) Scale is also an issue, as larger projects utilizing smaller ruled surfaces may appear as compound
curved as Gehry’s work exemplifies. The attempt to develop this project through ruled surfaces suggests that the successful use of ruled surfaces is more a part of conceptual development, accepting the material constraint of curving in only one direction.

Figure 9. Option One: Developable Surfaces

Figure 10. Option Two: Bi-Cubic Surfaces

Option Two: Flattening Compound Curvature through a Software Approach

The software approach to flattening compound curvature was previously the purview of advanced aerospace, automotive, and aeronautical software and therefore presented a daunting learning curve to mention nothing of expense. With the recent introduction of Lamina Design software, this has changed9. This stand alone, single function software is both inexpensive and easy to use. Unique to this software, is its ability to flatten compound curvature based on material density and thickness. This is intended neither as a product endorsement nor software tutorial, but this direction would not have been pursued without Lamina. The illustrated examples on the Lamina website are of smaller sculptural objects and furthermore are objects formed by only the surface. This is problematic as architecture obviously deals with much larger pieces and is always a composite of multiple systems. For Lamina to work, surfaces must be rebuilt as a mesh thereby dropping the iso-parametric information. However, through the piecewise technique of bi-cubic patches presented here, the boundary condition is all that is necessary so long as it is proportionate to the material process employed (e.g. in this example a 4x8 sheet of plywood with a 4x8 CNC router). Although this may appear as merely procedural, all too often I have encountered an indifference to surface construction stemming from the digital model as only a representational model of form expecting the software to do it for you. In this way, this is not a critique of this particular software, but supports the need for the digital process to be informed by the material process – an intelligence from the designer, not the software.

Material Technique: Routing Uniform B-Splines at Lines of Stress

For clarity, this paper has presented a linear process of moving from digital to material, with the knowledge of the material parameters, such as a unit size, informing the digital process. However, as both the digital process and material process were being tested at the same time, it cannot be stressed enough that the material development proceeded in tandem with the digital development. While a great deal of research was geared toward the digital technique of intelligently rebuilding the NURBS geometry, an equal amount of physical research was based on the ability of the material to form a compound curve as well as simply testing the file translation process from digital to material processes. This project proceeds with plywood as the material of choice for a number of factors, but particularly for the ease of use of working with wood, its relative inexpensive cost, and most of all that I had unlimited access to a woodshop with a 3-axis CNC router. Certainly other materials could be used and their specific properties would modify this process.

Test Patch

A small test patch was fabricated as an initial demonstration of this process. Curvature analysis
was used in Rhino to locate the patch with the most extreme curvature. From this analysis, a section of this patch and frame was flattened with Lamina. The frame was simple to fabricate and assemble with dados at the corners to register the pieces. For the 3/4\" structural skin, a technique was necessary to selectively remove material at regular intervals relative to the double curvature desired, which was a particular challenge as all four edges were of unique curvature due to unrolling the compound curve patch. Although it added for a complex workflow, the solution was easy: use the blending function in Adobe Illustrator. This function rebuilds these lines as a blending of uniform b-splines, whereas the differential geometry of NURBS is formed by the non-uniform basis of isoparms. These paths were then milled using a 3/4\" ball endmill to a depth of about 5/8\" of a 3/4\" piece of plywood. A ball endmill was used instead of a square endmill to avoid stress failure at the internal corners. This patch was then easily screwed to the frame. This quick sample identified three issues for further development. First, the blending lines were more dense than necessary in one direction, but more importantly were not dense enough in the second direction creating a noticeable segmentation at the edges. Second, the material does not naturally want to bend in both directions, and therefore formed a flat spot at the center of the approximately 1\' by 2\' sample. Third, although the skin is inherently stronger as a result of the compound curvature, because of the routed grooves it easily supported about 30 pounds, the weight of a child, but began to crack upon my full weight.

The structural integrity of the skin was of utmost concern and two options were considered. The first was to infill the cavity with polyurethane foam which expands creating an insulated and potentially rigid structure. The second was to laminate a thin sheet of material to the grooved plywood such that the grooves could not flex. A sheet of 1/8\" masonite was milled to the same flattened path profile, glued to the plywood and then screwed to the frame to dry overnight. After removing the screws, the laminated skin maintained the exact shape of the frame, and the new shell would support my full weight without cracking and minimal deflection. This introduced a more robust approach toward a true structural skin independent of an intermediary frame, and therefore this option was pursued in this project.

Through this move toward lamination, an obvious option of using several thinner sheets would eliminate the need for the grooves. Although this is a viable option, it was avoided in the attempt to minimize the number of pieces and the more complex apparatus required to laminate multiple sheets together. Moreover, as thinner material was more flexible, it also meant an increase in density of support structure for fabrication possibly even necessitating a continuous mold, which was to be avoided in the first place. Finally, the thinner laminations resulted in nearly double the material cost as thinner sheets are not priced proportionally to their thickness. Therefore, it was desirable to develop a technique mating two skins each with an exposed exterior face, unlike the laminated sample above with 1/8\" masonite. It was decided to laminate two skins of 1/2\" wood considering particle board, plywood sheathing, and veneer plywood.

Figure 11. Curvature Analysis

Figure 12. Test Patch Exterior
If the frame was not to be used in the final installation, could it be avoided all together? Theoretically, if there was a way to register the two offset shells through pins or dowels, the frame could be avoided. It must be made explicit that this would only work if the two skins were offset in the digital model and precisely flattened taking into account their thickness resulting in the slightest dimensional variation. Yet as a result of the surfaces being offset from each other, they share the same surface normals - that is, any line drawn perpendicular to the surface would likewise be perpendicular to the offset surface. Therefore, when these sheets are flattened, a hole drilled perpendicular to the surface would then become normal to the surface when the pieces take their shape. More significantly, if the holes are precisely placed, the holes should align only when the surface takes its shape and could be doweled fixing their position. Holes were proportionately located based on the same blending lines developed from Adobe Illustrator, only now the blend was made more dense to create a pattern of grooves and alternating holes. The ability to register the two laminations through dowels proved indispensable in laminating the skins, however it proved impossible to wrestle the wood into compound curvature without the frame. The frame then really becomes a stretcher and also a physical check that the skin is at precisely the correct curvature. If the previously described option one, of using ruled surfaces was used, this same technique of hole alignment and peg registration could be used without a supporting frame or mold, as the wood has no problem curving in one direction, so long as there is minute movement between dowel and hole, including material flexure.

In addition to the need for lamination, the test patch revealed two other issues, one regarding visual segmentation as a result of the grooves, and
second, a flattening of the material at its unsupported center. Numerous material studies were made on 1/2" 3 layer cabinet grade birch veneer plywood and 1/2" particle board adjusting groove spacing and depth, testing for flexibility. As plywood is not an isotropic material, the grain direction of the laminations has a significant impact on its ability to bend, and therefore deeper groove depths were tested perpendicular to the strength of direction. While particle board is more iso-tropic than plywood, it has almost no flexural strength and therefore segmented or slightly cracked at the grooves. Exterior plywood sheathing was briefly tested, but is rarely perfectly flat and therefore difficult to precisely mill the grooves. Furthermore, plywood sheathing has numerous knots, plugs, and internal voids that resulted in failure. For the project developed here, it was decided to proceed with 1/2" cabinet grade veneer plywood with grooves spaced at maximum of 3" on center, and 3/8" depth, leaving 1/8" of material, or about one of the three laminations. Further structural analysis may suggest alternating the grain direction between layers. However, as plywood generally comes with the grain strength in the long direction, to alternate the grain directions the piecewise construction of bi-cubic patches would have to be based on a 4'x4' max module and not the 4'x8' max module used here, doubling the number of pieces and therefore compounding the number of joints. The flattening of the material at its unsupported center was simply overcome by adding an intermediary vertical b-spline support in the final frame.

Frame Final Assembly

The frame itself demonstrates the direct translation of iso-parametric information to material structure. While orthographic slicing yields a series of flat sections, utilizing the iso-parametric lines yields ruled surfaces. These lines were offset 4" for structural depth, and digitally modeled as a modular series of nine frame patches. These frames were then unrolled, and tested in a laser cut scaled physical model. This physical model indicated a sequence of construction, as well as the need for curved corner bucks to give the boundary of the frames their correct curvature, and was instrumental for assembling the full size frame, suggesting that the model is not merely for representation, but a prototype of actual construction. The precise location of each plywood spline was marked with dados.

Modular Skin: Design for Assembly

The full size frame was left assembled as skin and joint options were tested on it. Through these numerous material and lamination tests, greater attention was placed on its surface quality creating a screen-like object at a scale between furniture and architecture. As a demonstration project, the grooves became articulated at the surfaces in conjunction with their structural necessity. Routing all the way through the material in one direction, the material took the curvature as well as expressing its construction. Similar to the dowels normal to the surface, the grooves only aligned as the panels took their shape.

As a full size installation/demonstration project, an additional constraint was to create an object that would easily be assembled, demounted and re-assembled elsewhere. This placed emphasis on a removable joint between the nine prefabricated panels. Several options were considered, including doweling, puzzle pieces, and a fingered spline joint. In the end, the simplest joint, a 1/2" lap joint was used. However, due to the size and geometry of these panels, a great deal of stress is placed on the joint, and therefore the simple 1/2" lap joint only became feasible when a system of post-tensioning was used in conjunction with the lap joint. By including vertical ball end grooves back to back, an approximately 3/4" round void was created, making it possible to run a continuous dowel in that void for additional support. However, a wooden dowel created too much friction, and was therefore impossible to remove. This introduced a new material to the project: high density poly propylene (HDPE). HDPE is relatively inexpensive, is very flexible, has a very low co-efficient of friction, with a high tensile strength, and is easy to fabricate. These HDPE rods were tapped at the ends and used as tenons to post-tension the panels which aided greatly in the assembly of the structure.

Skin Final Fabrication

The final fabrication of this project was no small affair, with the frame fabricated over spring break, and the laminated skins fabricated at the end of the academic year when the wood shop was more or less vacant. Laminating each patch over the frame was a blend between choreography and chaos. Each patch required at least ten clamps that were sequentially tightened to distribute the
The motivation of this research project is based on the relation of the material process on the digital process. In particular, through the mathematical and historical review of NURBS surfaces, it is found that there is a strong correlation between NURBS and material processes moving architecture beyond representations of form toward physical processes informing form and enabling the design process. The emphasis of this paper has been on the digital technique of developing conceptual NURBS geometry into piecewise bi-cubic patches informed by material stress as uniformly as possible. However, despite the rigorous digital process and numerous smaller test pieces, the full size patches built-up enough surface tension along the larger surface that each piece buckled at one fairly consistent location. Despite the frustration of this physical failure, pushing the material to its limits is also indicative of the need for further material research in tandem with the digital techniques presented here. One of the three bays was able to be assembled as a demonstration of the potential of this installation.

**Conclusion**

The motivation of this research project is based on the relation of the material process on the digital process. In particular, through the mathematical and historical review of NURBS surfaces, it is found that there is a strong correlation between NURBS and material processes moving architecture beyond representations of form toward physical processes informing form and enabling the design process. The emphasis of this paper has been on the digital technique of developing conceptual NURBS geometry into piecewise bi-cubic patches informed by material stress as uniformly as possible. However, despite the rigorous digital process and numerous smaller test pieces, the full size patches built-up enough surface tension along the larger surface that each piece buckled at one fairly consistent location. Despite the frustration of this physical failure, pushing the material to its limits is also indicative of the need for further material research in tandem with the digital techniques presented here. One of the three bays was able to be assembled as a demonstration of the potential of this installation.
parameters and processes into a materially related digital model. From this, two options are presented: one in working with ruled surfaces and one in working with compound surfaces. A material technique of routing uniform b-spline grooves was used to develop the directional material properties toward compound curvature.

As a result of the material failures in final fabrication, one of the conclusions of this research is that working with ruled surfaces and compound curved surfaces is more than simply a question of degree reduction, mathematically speaking, but a fundamental question of material resistance – a parameter not included in the “material parameters” of the digital model presented here. While the digital techniques presented here are an important development of integrating digital and material techniques, the material techniques require future work with emphasis placed on the
material resistance inherent in the material as a result of the curvature. Material research needs to focus on material composition: iso-tropic vs. non-iso-tropic materials, material density, and thickness of laminations in compound curvature. In addition to wood and metal, this would include new materials such as the HDPE introduced in this project. For prefabricated assemblies, structural testing is necessary through computational processes such as finite element analysis (FEA) as well as physical destructive testing on entire assemblies including the joints between assemblies. Building applications in polyurethane injected compound curved stressed skin panels as well as compound curved concrete formwork are two clear structural applications utilizing the techniques presented here.

Notes

1. The ease of interface is the question of bias, as Serriano argues, to say nothing that NURBS could be said to be biased from the first.
2. To the degree that “Form Follows Software,” at issue here is the development from form to fabrication and not the formal morphogenesis of these projects. See New Technologies in Architecture and Digital Design and Manufacturing, for the morphogenesis of these projects.
3. Frank Gehry’s Conde Nast project uses a similar approach with its glass surfaces while using ruled surfaces for the titanium interior. See New Technologies in Architecture and Digital Design and Manufacturing for more on this project as well.
4. Ironically, I was first introduced to Coons surfaces through MasterCAM.
5. As a result of the scale of architecture, this typically means an increase in isoparm density, if a reduction of isoparm density is required, this will most likely alter the surface.
6. Alternatively, it may be possible to split the surface at the isoparms as in Rhino. However, the accuracy here is questionable. Trimming the surface is not an option, as trimmed surfaces merely mask the entire mathematical surface from view.
7. See also Bechtold, Martin. “Surface Structures: digital design and fabrication” in Fabrication: Examining the Digital Practice of Architecture.
8. See www.rhinoceros3d.com, Rhino is well known for its unique “unroll” command to unroll developable surfaces.
10. This remains a viable option for future work as well as product application, but this project moved toward the more demanding application of a structural skin.
11. In hindsight, the largest pieces that approached 8’ were also the most prone to failure both from their own weight, as well as surface tension developed over the longer length of the piece, and therefore, alternating laminations on a 4’x4’ max module may be more successful.

References


