AC 2009-904: COMPUTER-AIDED PHYSICAL MODELS: INTRODUCING NURBS AND FABRICATION IN CONCEPTUAL ARCHITECTURAL DESIGN PROJECTS

Stan Guidera, Bowling Green State University

Dr. Stan Guidera is a registered architect and an Associate Professor in Architecture at Bowling Green State University. His areas of specialization are in Building Information Modeling and design visualization.

Abstract

This paper documents the activities and outcomes of an advanced architectural computing class that was modified to introduce NURBS (Non uniform rational b-spline) based design tools along with 2-D and 3-D fabrication and rapid prototyping techniques. Two class assignments were used to introduce this content. Project outcomes are documented along with recommendations for faculty considering introducing similar content into their courses or curriculums.

Introduction

The activity of design is rooted in an iterative process through which concept evolves both linearly and non-linearly from conceptualization to material form. Inherently, all design proposals undergo a transformation in the process of evolving from the conceptual stage to a level of refinement in which the initial concept can be transformed into a proposal that is buildable. In this process, parameters such as structure and other constraints require the designer to modify or even re-conceptualize the design concept. For example, design development phase of the initial proposals for Jørn Utzon’s Sydney Opera House required that the parabolic curvature of the shells be significantly modified to accommodate the construction technologies available at the time it was built [1]. According to Kloft “finding a structurally optimized and geometrically clearly defined form was a necessary condition for realization of double curved surfaces in pre-digital times [2].

However, recent advances in design and construction technologies have transformed the limits of architecture, engineering, and project delivery. There has been “an extension of the formal freedom in architecture” [2]. Writing on the topic of “Engineering Form”, Kloft stated that “the emerging digital design and production environment, combined with new materials and modern technologies, makes possible unprecedented challenges in the repertoire of formal language” adding that “boldly curved shapes, a few years ago thought of as unrealizable and thought of as pure fantasies, can now be built.”

These advances reflect contemporary discourse in architecture, which has seen a shift towards a more topological conception of form and towards non-Euclidean shapes and non-discrete volumes that would have been inconceivable without advanced computational tools [3] [4]. According to Kolarec, “technological architectures are being replaced by computational architectures of topological non-Euclidean geometric space, kinetic and dynamic systems, and genetic algorithms” [3]. Similarly, Zellner stated that “architecture is recasting itself, becoming in part an experimental investigation of topological geometries, partly a computational orchestration of robotic material production and partly a generative, kinematic sculpting of space” [5].

This shift is attributed to the adoption of software applications that have been “appropriated” for architecture from other disciplines [4]. This is evidenced by Frank Gherys’ use of Catia, software
originally developed for the aviation industry \cite{6,7}. The digital tools that are facilitating this departure are based on the use of NURBS (Non-uniform rational B-splines, where the b refers to Bezier splines). NURBS were developed for engineers needing mathematical precise definitions of free-form curved surfaces for computer aided design in aviation and automotive industries. The underlying mathematics used to generate NURB curves and surfaces differs from conventional vector-based CAD in both precision of curve and surface representation and in ease of manipulation. NURBS produce “topological, ‘rubber-sheet’ geometry of continuous curves and surfaces” \cite{3}. NURB geometry is represented “not by implicit equations, but by parametric functions, which describe a range of possibilities” \cite{8}. In describing NURB geometry, Kolarec stated that the “shape of a NURBS curve or surface is controlled by manipulating the location of control points, weights, and knots…. NURBS make the heterogeneous, yet coherent forms of the topological space computationally possible” \cite{3} (Fig.1). Despite the complexity of form, the geometry is also relatively simple to manipulate. As described by Kolaric, “by changing the location of control points, weights, and knots, any number of different curves and surfaces could be produced \cite{3} (Fig. 2). NURBS applications also typically support complex curve-on-surface operations (Fig. 3), surface-offset operations (Fig. 4), and complex surface trimming operations (Fig. 5).

These advances in digital tools, combined with the re-conceptualization of architectural form, are producing a formal complexity in built works that would have previously been impossible to conceive and construct. Therefore, in parallel with the re-conceptualization of architectural form, there has been a similar shift in the role of structure. In addition to examples such as Gehry’s pioneering work with digital technologies in architectural production, projects by Cook and Fournier \cite{2} (Fig. 6), and Douglas Garofalo \cite{9} illustrate the influence of these developments on the built environment. However, the form of projects such as these suggest that, in such projects, structural innovations required for such forms have yielded a new structural aesthetic derived from the collaboration and integration of the process of structural design and architectural design associated with such design proposals \cite{2}. The collaboration between Norman Foster and ARUP Engineering \cite{10} (Fig.7) serves as a pre-eminent example, and has yielded several significant built works that have re-defined the role of technology in design and the discourse between the formal and the constructible.

The use of NURBS-based modelers in architectural design provides the potential for students to explore design options that were to a large extent inconceivable in the context of conventional design processes using conventional vector-based computer aided design and drafting tools. Therefore, design projects with an emphasis on structure in an applied sense could inherently restrict students to proposals that were limited by their current technical knowledge and as a result inhibit the degree to which students would explore unconventional form and massing afforded by NURBS geometry.

In response to these issues, a design project was developed to investigate the extent to which student design proposals developed using NURBS-based geometry were transformed by the limitations of a physical materiality. Based on the premise that the primary studio learning outcomes included enabling students to gain experience with a design-development process with external constraints of materiality and construction, the project required students to develop their design proposals utilizing digital modeling combined with computer-aided fabrication, thus
integrating physical iterations of their proposals into project requirements and submissions as well as providing a direct connection between the modeling environment and the physical iteration. The class used in this investigation was an elective computer-based design class for third and fourth year architecture majors taught concurrently with design studios. There were 19 students enrolled in the course, with 9 third-year students and 10 fourth-year students. The projects documented here comprised approximately 60% of the course content, with the other 40% allocated to computer applications largely unrelated to NURBS modeling. Two digital modeling tools were utilized, both of which introduced specific limitations. A laser engraving system, which uses vector data to cut model components from crescent board and other similar materials, required students to extrapolate model curvature to planar surfaces and adjust their proposals to generate developable surfaces and to facilitate assembly. A 3D printing system, which utilized stereo lithography files to generate model components from ABS plastic, required students to evaluate their proposals in terms of optimizing support structure necessary for the model components to be physically produced.

**Digital Fabrication and Prototyping in the design process.**

Models have traditionally served as a key tool in the design process, historically serving as an intermediary between complex design ideas and the construction workers [11]. However, digital fabrication has several advantages over traditional modeling processes for both professional and academic environments. Sass and Oxman proposed that “digital fabrication for designers offers realistic opportunities for shape representation, evaluation and redesign of complex design initiatives”, and added that “one asset worth noting is that digital fabrication extends learning in a digital design environment by engaging the designer with materials and machine processes similar to those used in construction”[11]. They also proposed that “the use of these appliances and software extends creative design beyond the early stages of design and supports the continuity of design through its various stages”. In addition to providing advantages for considering design and material options, it also supports knowledge acquisition [12].

The two fabrication processes used in the project were laser engraving and 3D printing. Each process required distinctly different approaches for producing physical models. The laser engraver used in the project was a Universal Laser Systems M200 100 watt laser (Fig. 8). The unit can accommodate material with up to 12”x20” with ¼”maximum thickness. The laser engraver process uses two-dimensional vector linework as a path for a laser cutting tool which can cut or etch flat pieces of a wide range of materials, including matt board, thin plywood, basswood, or acrylic. Individual pieces are cut and then manually assembled. Cutting is controlled by the speed at which the laser moves along a path and the intensity of the laser power settings. These settings are controlled by assigning power and speed attributes to different colors in the vector file. Higher power settings and slower speeds are used to cut through a material, while lower power settings and higher speeds are used to etch or engrave material surfaces. Etching can be used to render surfaces with considerable detail for material representations such as masonry lines and mullion trim.

This process can be very effective for producing components that are assembled to represent conventional architectural form (i.e. Euclidean volumes and regular orthogonally oriented geometry) which is composed of planar surfaces such as walls and slabs and readily represented
by a planar surface or model component. However, complex curved forms must be approximated via a series of planes, analogous to creating topography models. Therefore, complex curved geometries with varying topologies such as NURBS-based surfaces can only be represented as rough approximations.

The 3D printer used in the project was a Stratasys 758 BST (Fig. 8) using Catlyst Rapid Prototype software. This model has a 8”x8”x12” build area and uses an ABS plastic-based material to create the model components. It is a stereo-lithography process involving two material components: a material that is used to create the actual model and a separate material that is used to build up a support structure for the model during fabrication. The material for the model and the support structure is supplied in two separate cartridges. Models can be created as a single monolithic form or from individual components that are then assembled. The software imports STL files, a file format that is supported by most modeling applications (Fig. 9). The STL format has been adopted as the standard by the rapid prototyping industry. In an STL format curved surfaces cannot be represented accurately since STL files convert geometry to an assembly of connected planar triangles or facets. By increasing the number of triangles used to represent a curved surface, the approximation of ‘smoothness’ can be increased, although this can significantly increase file size \[12\]. When optimized, 3D printers can provide an effective medium for producing physical models of geometry composed of curved surfaces and forms.

3D printing processes can be broken down into five stages. First the model geometry must be imported into the software driving the 3D printer. Second, the software must be used to adjust the smoothness approximation. Stage three is a pre-processing stage that slices and prepares the STL file to be built based on the size and orientation of the geometry. This operation is critical because where the design is placed on the build platform influences both the piece’s strength as well as the time required to build the model. It can also influence cost as the amount of material used to build both the model and supporting structure can be influenced by the orientation. The fourth stage is the actual construction of the design and the fifth and final stage is post-processing, in which the design is removed from the machine and detached from the supporting structures \[13\].

Modeen \[13\] documented both pros and cons for rp processes which would be categorized as 3D Printing. He cited the ability to produce complex and detailed three-dimensional forms and the reduction of lead times for unique parts as key advantages. Disadvantages included slow build-speeds, limitations on the size of objects one is able to produce, limited available materials, and the final surface quality usually needs some secondary finishing. It is the ability to create physical representations of complex forms that is particularly relevant to this project.

**Project description and parameters**

The software used in the project was Rhinocerous3D 4.0, a free-form NURBS modeling application. Originally developed as a plug-in for AutoCAD, Rhinoceros 3D is a stand-alone commercial NURBS based modeling tool used in a broad range of industries \[14\]. This software was selected over other applications with NURBS capabilities (3D Studio Max and Maya) available to the students in university computer labs for four primary reasons:
Rhino provided an exceptionally robust NURBS modeling environment with extensive surfacing and editing capabilities for splines and surfaces.

The interface is intuitive but also includes many similarities to AutoCAD, thus facilitating the transfer of students’ pre-project skill set and familiarity with AutoCAD to operations with Rhino. Similarities include an extensive set of icon-based toolbars, a command-line interface that provides users with instructions and feedback, similarities in command nomenclature and syntax, similarities in coordinate-input syntax, and AutoCAD-like layers and blocks for organizing model geometry.

Legacy of use in fabrication in rapid prototyping. Extensive file export capabilities, including formats commonly used with rapid prototyping hardware devices and related software such as stl and acis formats required for driving 3D printing equipment.

Extensive vector-based file export capabilities required for use with the laser engraver.

Rhino generates robust STL files and also includes STL error checking utilities.

**NURBS Project One: Pavilion Project**

NURBS Project One involved two phases. The initial task was a design project with limited program requirements in order to provide a framework that facilitated formal explorations by the students. Students were not informed in advance that the project would require them to use their digital representations as a basis for fabrication. A site was not specified for either task. The project parameters were structured to require students to utilize a diverse range of 3D NURBS modeling operations intended to reinforce the following concepts:

- Control point manipulation of curves and surfaces
- Surface generation using extrusions, sweeps, and blends
- Surface generation using lofting
- Volume generation using surface offsets
- Iso-curve operations
- Edge and curve projections onto another surface

The program required students to create a canopy structure that would function as bus stop and park pavilion using a nubs surface that was to cover up to a 150’ x 150’ rectangular area with a minimum clearance above the ground plane of ten feet and a maximum clearance above the ground plane of 30 feet which does not connect (or touch) the elevated ground plane (see below). The proposal was to suggest either a structural skin via a two directional system with “logical” spacing or a surface supported by a logical system either above (exterior) system or below-surface (interior) system the canopy. Each proposal was to incorporate a supporting column system that was integrated functionally as well as aesthetically with the canopy. Each proposal was to incorporate an elevated ground plane which covers the same area of the ground as is covered by the structure above. Program components included a service core enclosure for vending and ticket dispensing.
To raise the issue of structural conditions associated with the proposed form, the project called for an integrated and “explicit” – i.e. visible - structural system. The structural system was to suggest a structural skin via a two directional system with “logical” spacing. Students had the option to develop the structure as an exterior system, an interior system, or any combination of both interior and exterior.

Upon completion of the initial design task, students were required to submit representations of their proposals. These included rendered orthographic views of the top (plan), a side view (elevation), and a sliced view (section). Two 3-D renderings were also submitted. All representations were to include a light source, shadows, and generic materiality, and all representations other than the top (plan) view required human-scaled figures to be included.

In Phase 2, students were required to reconsider and adjust their proposal with the emphasis specifically on the canopy surface based on developing a physical model using a vector based laser-engraver and to introduce the concept of developable surfaces. This two-step project required the students to render their canopy surface proposal, test the surface for being developable, and then produce a physical representation of the 3D surface using the laser engraver. A developable surface is one which can be flattened two dimensionally in order to fabricate that surface using materials such as sheet metal. Therefore, the introduction of concepts related to developable surfaces was deemed critical in that it would be directly related to the class activity and support class content related to fabrication processes and techniques. The physical model was to represent the surface and the surface support structure. No parameters were established for supporting the physical model, based on the assumption that this would provide students with more flexibility to accommodate their specific modeling proposal.

**NURBS Project One Outcomes**

The first phase of project one proved successful and the activities were entirely separate from any physical modeling. The students had minimal difficulty developing competencies with the NURBS modeling software (Rhino 3D). Transfer of AutoCAD skills was identified by students as an advantage. Students were observed to have a preference for visual control point manipulation of the NURBS curves and surfaces over using keyed-in coordinates since the project parameters did not emphasize detail and precision. Additionally, prior experience with other applications which were characterized by direct manipulation of geometry (i.e. Sketch-up, 3D Studio MAX) was also identified as a factor in ease of developing competencies with Rhino. There were three students with minimal experience with applications beyond AutoCAD and all three had a steeper learning curve in using the NURBS application.

Several proposals were very successful in terms of mastering the advanced modeling strategies. However, it was noted that many proposals included doubly-curved surfaces, which are inherently undevelopable. Therefore, it was anticipated that complications would arise in Part two with building physical models using the laser engraver. Examples of Project One – Phase 1 submissions are documented in figures 10 and 11.

The second phase of project one proved more challenging for all students. Since a primary outcome was to encourage students to explore the potential of NURBS modeling, no limitations...
on surface geometry was added, even though it was evident many students would likely have proposals that would be difficult to translate to the intended modeling technology. As anticipated, the geometries generated in most Phase 2 proposals utilized doubly-curved surfaces. Further, most students perceived that the extent of revisions which would be required to insure that the surfaces were developable compromised the visual characteristics of the original proposal. As a result, all 19 of the students chose to pursue alternatives that were presented, including utilizing Rhino 3D “flattening” operations which produced an approximated 2D representation of the original surface. In other cases students utilized a free plug-in (Arch-cut) which panelized the surface. Both strategies proved to be effective for generating the 2D geometry needed for creating physical model components with the laser engraver. The physical models that were produced varied in terms of quality, and many students had difficulty creating adequate support structure for suspending the surface. A Phase 2 submission is documented in figures 12 and 13.

NURBS Project Two: NURBS office tower

The second project was also divided into two parts. The project was to be first conceptualized at an urban (city) scale (phase 1), and then re-conceptualized at a human scale (phase 2). The assignment required students to design an office tower for a specified site with an emphasis on creating an “object building” in an urban context. The aesthetic expression of a NURBS generated building skin was a primary objective. Several programmatic criteria were specified, including limitations on setbacks, building height, floor to ceiling heights, floor slab thicknesses, and minimum building areas. Once their design was completed, students were required to create three physical prototypes for Phase 1. Two of the prototypes were to use the laser engraver to produce models that represented the building form using a series of both horizontal and vertical slices. Unlike project one, the use of doubly-curved surfaces would not be a factor as there was no criteria requiring the use of developable surfaces. The third prototype was to be produced using a 3D printer, which raised several new technical issues for the students. The 3D printer creates a model using the stereo-lithography (.stl) file format, which is essentially a triangulated mesh. More importantly, the geometry must be closed and “water-tight”, meaning that the precision level must be very high in order to avoid any gaps between the edges of the triangulated faces. Therefore, all modeling operations must be inherently precise. Voids or gaps between adjacent surfaces would produce an invalid mesh and would be unusable for 3D printing. It was intended that the more rigorous modeling parameters in this project would enable students to further develop skills with NURBS modeling while simultaneously providing the opportunity to expand course content to include additional fabrication concepts. Students were required to document the amount of material used, the amount of support material used, and the time required to print the model.

For Phase 2, the students were to take the urban scale “office tower” created for phase one and convert the model to “human scale” as a “NURBS bench – high rise as chair” based primarily on their experiences and skills developed in creating the first two “sliced” representations of the office tower. After the physical models generated with the laser engraver were finalized, the instructional strategy intended to have the class vote to select four projects from the Phase 1 submissions, with each selected project assigned to a group of students. Each group had two weeks to present a proposal for creating functional bench, to be built and installed on campus.
Their proposal was to include a proposed fabrication strategy, a material list and cost estimate, and documentation of their proposals assembly processes and sequences using 2D and 3D digital models. The Final project was to be selected by a jury of faculty and was to be subsequently built and installed by the entire class. In addition to a requirement that the “bench” must reflect the aesthetic character of the original office tower other parameters were added. The structure was to be for an interior display/function and the seat structure must accommodate at least one person. Reflecting prior activities in the project, the structural system was to be two directional—a combination of the horizontal and vertical modeling strategies. Materials were to be plywood with bolted connections (stainless steel only) along with other materials such as plastics, wood dowels, and other woods or metals as needed. Each group was asked to document any revisions made to the office tower geometry.

**NURBS Project Two Outcomes**

As anticipated all students were successful in producing a solution to the programmatic parameters of the high-rise and in generating computer models (Fig. 14). Additionally, the first two prototypes, which were to be created using 2D slices, also were perceived by students and faculty to be effective as physical representations of the complex curved surfaces used in the computer modeling for the office tower proposals (Fig. 15). However, several students had significant problems in creating the .stl meshes appropriate for 3D printing for creating the third prototype. There were two primary issues identified. First, several students had problems in optimizing the resolution used in exporting, resulting in excessive file sizes with resolutions set too high or surface triangulations that produced excessively large faces which reduced surface curvature to an unacceptable level and/or yielded unacceptable gaps between the edges of adjacent polygons. Most of these complications were attributed to inconsistent scaling operations as the geometry was reduced from virtual full-scale dimensions of approximately 300 feet in height to a scale of 1:100 in the 3D printer. In response a sequence of operations was established with prescribed steps and settings. Other complications resulting from projects starting out with mesh tolerance options being set too low also were found, and in most cases required students to re-model their proposals.

The second issue that arose was also related to meshing complications but was more clearly associated with modeling errors by the students rather than software settings. The file exporting functions in Rhino3D are very robust in that it has native capabilities to write a wide variety of file formats. Additionally, the .stl export functions of Rhino include mesh-checking, which is intended to flag geometry that will generate .stl mesh errors. In practice, many students were able to identify mesh problems and remodel the geometry. However, some project geometry that was exported without errors still proved to be unusable in the 3D printing process. In most cases students were given alternative modeling strategies to repair their models. It was also determined that this problem provided an opportunity to introduce additional course content related to mesh repair concepts and using external mesh repair applications. It must be noted, however, in two cases the geometry was never adequately repaired either through improved modeling techniques or using mesh repair tools and plug-ins.

The tower-to-chair project proved to be effective at introducing additional parameters to the class activities, notably a real-world dimension in which the physical product of the assignments has...
more far reaching implications than a scale model representation. In most respects, based on student comments, this activity was the most relevant of the class assignments in terms of students making a tangible connection between the class and real-world applications for creating form using NURBS technologies (Fig. 16, 17, 18).

Summary and Recommendations:

Faculty and students felt the class assignments were effective in meeting the stated goal of providing a foundation in NURBS modeling concepts and the use of NURBS geometry in generating complex and untraditional architectural forms. While no quantitative analysis of outcomes was conducted, the number of students that utilized NURBS applications in subsequent studio projects for all or part of their design exploration and documentation activities suggested that the skills developed in the assignments were being applied by students. Of the 21 students participating in the class, 20 were utilizing Rhino 3D for all or a substantial part (50% or more) of their conceptual design and design development activities in the studio course immediately following their computer modeling courses, and 12 were utilizing one or more of the fabricating strategies used in the class, including 3D printing. More importantly, the use was evenly spread over third and fourth year students.

However, the complications that arose do suggest that faculty contemplating similar assignments may want to consider:

1. Provide experience with software that utilizes direct point/edge manipulation of objects prior to the introduction of NURBS modeling concepts. The students in this class without such experience had a longer learning curve and required additional out-of-class time to stay on task. Therefore, assessment of strategies for introducing digital applications in the overall curriculum must be re-assessed to optimize student learning in courses with content related to NURBS-based curricular content.

2. Faculty should assume some if not all students will incorporate doubly-curved surfaces and other geometries that inherently preclude the use of developable surfaces. Therefore, while including course content related to developable surfaces is an essential concept for a design class that is also introducing digital fabrication concepts and methods, assignments and outcomes should be developed based on the assumption that alternative 3D – to 2D operations will be required.

3. In order to accommodate course objectives similar to those outlined in the class documented in this paper, faculty will need to adjust course content to accommodate this inclusion of .stl file analysis and repair applications is essential for assignments requiring complex volume to 3D printing processes.

4. Plug-ins (externally developed 3rd-party applications that extend the original application’s functionality) proved to be an important asset for most students’ projects. Therefore, faculty investigation into the available plug-ins for the application(s) used in the class may be necessary in order to allocate class-time to cover the use and operation of relevant plug-ins.
that students may find necessary to complete the assignments.

5. The time required for 3D printing of student projects can be reduced if multiple project model geometry can be combined in a single printing process. However, this strategy must assume that the surface geometry for each project is watertight with valid meshes and ready for 3D printing. Therefore, faculty should allocate additional time for covering content related to creating valid geometry or allocate additional time to the 3D printing process.

Conclusion

The faculty felt the primary measure of the project’s success was in the proliferation of the use of NURBS geometry throughout subsequent studio projects, and the extent to which students were readily able to utilize the fabrication strategies employed in the class in modeling and design communication. However, concerns have surfaced that the visual appeal of the geometry generated with these technologies may adversely influence student’s design strategies if the use of the digital tool itself takes precedence over the search for an appropriate solution. Therefore, it is critical that faculty emphasize that complex surface modelers are only one of many tools to be utilized in design exploration and that, unlike the projects in the digital studio course discussed in this paper, they take care to structure studio assignments that are inclusive of a variety of responses rather than one in which the use of a specific digital tool is inherent.

Bibliography

Figure 1. NURBS control points on curve (left) and surface (right)

Figure 2. NURBS control points: Surface post-manipulation
Figure 3. NURBS curves on surface operations.

Figure 4. NURBS surface offset operations.

Figure 5. NURBS surface trim operations.
Figure 6. P. Cook and C. Fournier. Kunsthaus Graz, Gallery for contemporary and multidisciplinary art. Graz, Austria. Architecture Week.com http://www.architectureweek.com/cgi-bin/awimage?dir=2003/1203&article=design_1-1.html&image=12321_image_1.jpg

Figure 8. Universal Laser Systems M200 (left), and Stratasys 758 BTS 3D Printer (right).
Figure 9: Stl file exported from Rhino3D. Triangulated mesh wireframe (left) and shaded mesh (right).

Figure 10: Project One Phase 1 submission: Canopy after flattening operations (left), Design Proposal (right)
Figure 11: Project One Phase 1 submission: Design Proposal Elevation (Left) and Perspective (Right)

Figure 12. Project One Phase 2 submission: Results and report of flattening operations

Figure 13: Project One Phase 2 submission
Figure 14: Project Two NURBS office tower proposal. Site elevation (left), Site plan (right).

Figure 15: Project Two Prototype 1 and 2 submissions.

Figure 16: Project Two Phase 2: Tower-to-chair project orthographic drawings
Figure 17: Project Two Phase 2: Tower-to-chair project

Figure 18: Project Two Phase 2: Tower-to-chair project