AD Structuring in Architecture

Special Issue on Architectural Structural Engineering 2010

Guest Editors
Prof. Dr. Arch. Rivka Oxman Prof. Dr. Arch. Robert Oxman

Architectural Geometry as Design Knowledge

Helmut Pottmann

Geometry has always constituted a basic knowledge in the architectural design process, but it has hardly ever formed an area of research. The event of freeform shapes in contemporary architecture has completely changed this picture. The geometry of architectural designs is getting more and more involved and challenging. Architects nowadays exploit digital technology originally developed for the automotive and airplane industry for tasks of architectural design and construction. This leads to a number of problems since the architectural application differs from the original target industries in many ways, including aesthetics, statics, and manufacturing technologies. The event of numerically controlled machining and other digital production technologies in the automotive and airplane industry resulted in a significant body of research on appropriate mathematical representations and algorithmic solutions. Its main findings form the backbone of state of the art 3D modeling software. A similar development for the architectural application has just started; the resulting area of research may be called *Architectural Geometry* (AG).

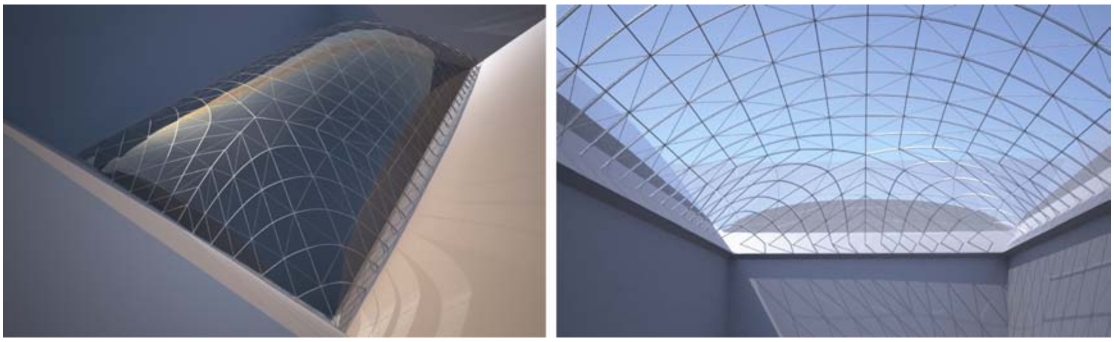
Research in Architectural Geometry aims at the development of new tools for the creation of digital models for architecture which meet the requirements in the shape creation and design phase and already incorporate basic aspects of the actual construction including material, manufacturing technologies and structural properties. AG also plays an important role in enabling a completely digital work flow from design to manufacturing, especially for highly complex geometries. Moreover, AG provides tools to transfer standard digital models into a form suitable for the architectural application and fabrication; this process is referred to as “rationalization” and discussed below in more detail.

Construction-aware geometric design vs. rationalization. A *construction-aware design approach* incorporates knowledge on the used material, panel types, sub-construction, etc., in the shape creation process via customized geometric modeling tools. As AG is not yet in the stage to deliver powerful software for accomplishing this approach, one often has to enter a kind of re-design phase after the original geometry definition; this is known as *rationalization*. Rationalization has to re-compute the geometry by minimally deviating from the original design and at the same time meeting requirements on panel types, smoothness of the skin, aesthetics of panel layout, cost of production and other aspects. From a mathematical perspective, rationalization amounts to the solution of often highly nonlinear and computationally expensive optimization problems. The development of efficient optimization algorithms and the incorporation into user-friendly rationalization software tools are big research challenges in AG. Methodology developed for rationalization also opens up new avenues for the creation of novel construction-aware design tools. AG research has strong roots in applied mathematics, computational science and engineering and can only meet its ambitious goals in a close cooperation with architects, structural engineers and construction companies. In the following, these general claims and thoughts shall be illustrated at hand of selected research results and by geometry consulting work of Evolute GmbH[1].

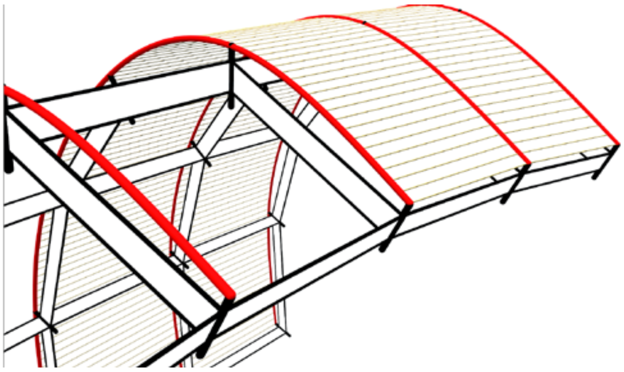
The trend towards high geometric complexity has strong implications on the geometry education as well[2]. Already the effective use of powerful geometric design software requires more geometry knowledge than traditionally taught, and an even deeper understanding of geometry is necessary to excel in the exploitation of parametric design technology.

Architectural freeform structures from single-curved panels. F. Gehry has been one of the first who employed freeform surfaces in architecture. The research performed in connection with his work is described in D. Shelden's thesis[3], which is also one of the first contributions to AG in the sense of the present article. Gehry used mostly developable surfaces. These surfaces, also known as single-curved surfaces, can be unfolded into the plane without stretching or tearing. They carry a family of straight lines, along each of which they possess a constant tangent plane. This implies various good properties for fabrication. Recent research[4,5] relates the coverage of a freeform surface by developable surface strips with work on quadrilateral meshes with planar faces. A technique composed of subdivision (refinement) and optimization towards developability provides a direct (construction-aware) modeling approach. Rationalization of a given freeform surface with developable panels (strips) follows related ideas.

An example of construction-aware geometric design. Combining subdivision and optimization (top) provides a direct approach to modeling freeform surfaces which are composed of single-curved strips. A result of this technique is shown in the two views of a research case study (bottom).

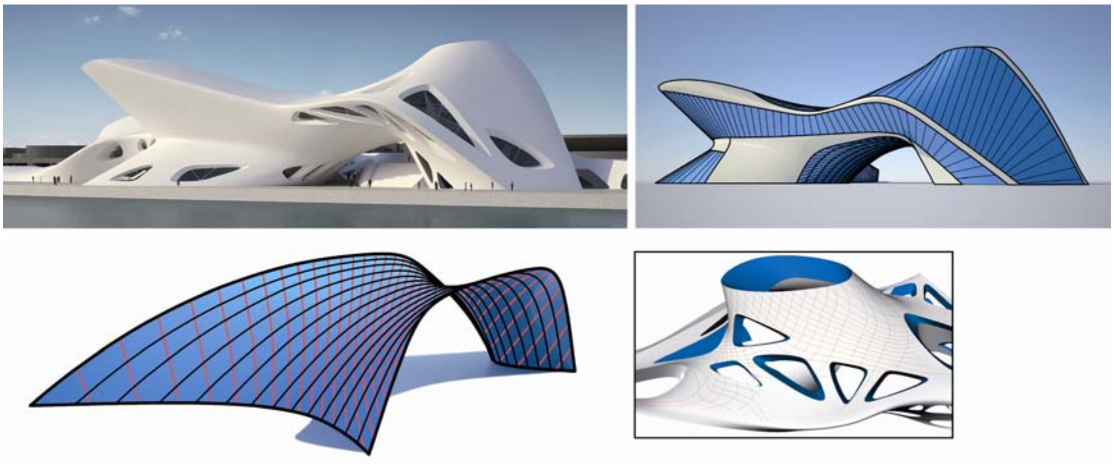


A simultaneous view onto geometry, structure and fabrication. Ongoing research by Evolute and RFR aims at a combined treatment of geometry, structure and manufacturing. This is illustrated here at hand of an example, a shell acting as a roof of a courtyard with rectangular base. The shell's shape and its rationalization into single curved (more precisely, cylindrical) panels were found by means of structural form finding combined with geometric optimization.



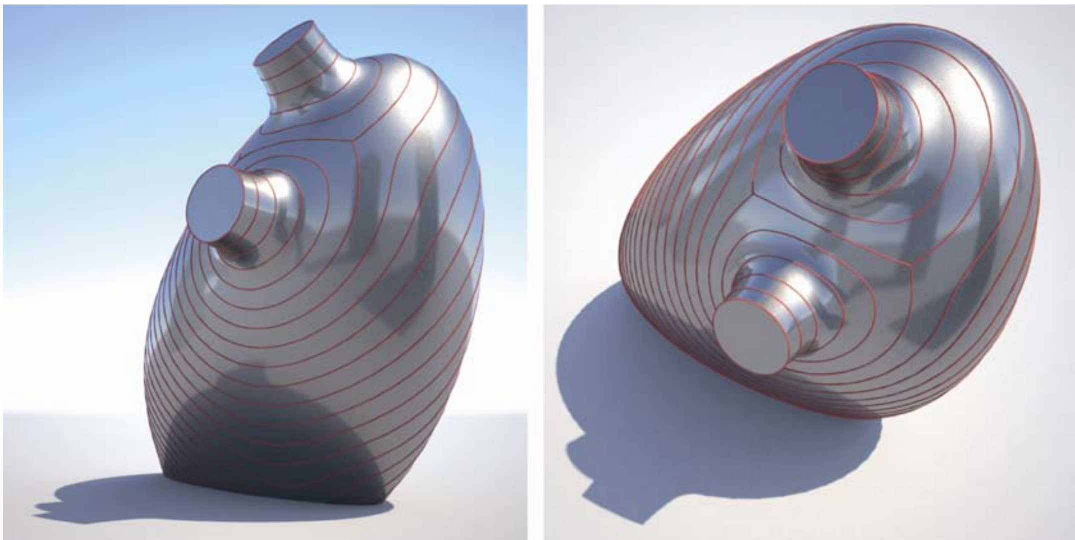
Coupling geometry and construction: The close relation between the coverage of a surface by single-curved strips and quadrilateral meshes with planar faces leads to the development of supporting structures with straight beams and well defined node axes for single-curved panel arrangements on freeform shapes[6].

Rationalization by ruled surfaces and relation to manufacturing technologies. Ruled surfaces are formed by a family of straight lines and therefore possess advantages in fabrication. To give an example, ruled panels from GRC (glass fibre reinforced concrete) can be produced more efficiently than general double curved panels, since the rapid and inexpensive hot wire cutting technique can be used to manufacture their styrofoam molds. Generically, ruled surfaces possess negative Gaussian curvature K, which means that they are locally saddle shaped; they may also be single-curved (K=0). Hence, designs which contain large areas with non-positive K are promising candidates for rationalization with ruled panels. Software for performing this task has recently been developed by Evolute. An example of its application is given by the Cagliari Contemporary Arts Center (Zaha Hadid Architects).

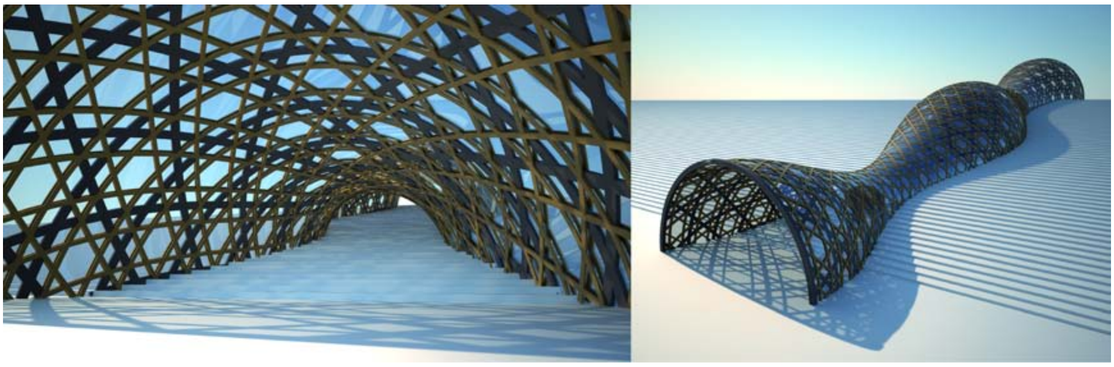


Cagliari Contemporary Arts Center (by Zaha Hadid Architects). This design contains large areas which can be covered by ruled surfaces (upper right), whereas more complicated saddle-shaped parts may be rationalized by a smooth union of ruled strips (bottom left). The asymptotic curves (curves with vanishing normal curvature) depicted in the lower right are partially nearly straight and thus indicate the potential for rationalization with ruled surfaces. The algorithmic techniques employed in this project are linked to manufacturing geometry (CNC machining) and hot wire cutting of molds.

Panel layout. Recent developments in manufacturing technology for doubly curved metal panels suggest that large-scale freeform metal façades will be buildable in the near future. This technological advancement will eventually simplify the rationalization of a metal façade surface, but splitting the surface into panels of maximum manufacturable size is still required. Software tools available on the market are not yet efficiently supporting the design of such panel layouts for complex freeform surfaces. In the paradigm of parametric modeling this often leads to freeform surfaces being replaced by simple parametric surfaces at an early stage. Recent research therefore tries to close these gaps, treating arbitrary freeform surfaces as parameters themselves and fully parametrizing their panel layouts.



Panelisation exploiting the power of non-regular connectivity. This panelisation of the Skipper Library example issued by Formtexx[7] is based on strips of nearly constant width and demonstrates how a non-regular connectivity of strips can be used to achieve this goal. It has been computed with Evolute’s panelisation tool.



Geodesic patterns on a freeform surface. On this surface, three curve families which are close to geodesics (shortest paths) are arranged in a trihexagonal pattern. Geodesic curve families are preferred for cladding with wooden planks. The trihex-arrangement of three such families is especially useful for the construction of timber grid shells. The computation of this example (by Evolute) is based on the same mathematical representation and optimization principle as that for the Skipper library example. So far, it is a pure result of AG, but future research will aim at combining geometric and structural optimization.

Conclusion and future research. Architectural Geometry constitutes a new and challenging research area which aims at providing construction-aware design tools and enabling a completely digital work flow from design to manufacturing, especially for highly complex geometries. While we have illustrated complex geometry mostly at hand of surfaces, future research also has to address fully spatial structures. The new tools which are currently being developed have built-in some detail knowledge in AG, but their efficient use requires a very solid basic understanding of geometry which goes beyond the content of a traditional geometry curriculum in architecture. Future work also has to address these new challenges in geometry education.

Notes.

1. see http://www.evolute.at
2. H. Pottmann, A. Asperl, M. Hofer, A. Kilian, *Architectural Geometry*, Bentley Institute Press (Exton), 2007.
3. D. Shelden, Digital surface representation and the constructability of Gehry's architecture. PhD thesis, MIT, 2002.
4. H. Pottmann, A. Schiftner, P. Bo, H. Schmiedhofer, W. Wang, N. Baldassini and J. Wallner, Freeform surfaces from single curved panels, ACT Trans. Graphics 27 (2008).
5. funded via Project 230520 of the FP7-IAPP framework; project partners: TU Wien, Evolute and RFR.
6. RFR S.A.S. and Evolute GmbH, Austrian Patent Application A1007/2008.
7. See http://www.formtexx.com

Helmut Pottmann - Short biography

Helmut Pottmann received a PhD in mathematics from Vienna University of Technology (TU Wien) in 1983. Since 1992 he is professor at TU Wien and head of the 'Geometric Modeling and Industrial Geometry' research group. He is currently director of the Geometric Modeling and Scientific Visualization Research Center at King Abdullah University of Science and Technology, Saudi Arabia. His recent research concentrates on Geometric Computing for Architecture and Manufacturing.