Computational and Optimization Design in Geometric Acoustics

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ABSTRACT

The use of 3D computer modeling tools through the 90’s has revolutionized the practice of Architecture. Coupled with new fabrication processes, these have introduced new territories for architectural design. Such techniques are also available to acoustic designers for the shaping of spaces. With 3D modeling programs such as Rhino3D and Grasshopper incorporating NURBS, geometries can be easily adjusted to meet both aesthetic and functional objectives. Control points of NURBS elements give access to the parameterization of geometries which subsequently can be assigned variables and open the way to computational design optimization. Through several performing arts project examples, this paper gives an overview of processes used today by acousticians to refine designs either through iterative design, auralization, optimization algorithms and real-time computer modeling. Contextualized with design practices from different periods of history, the paper discusses the relevance of computational and optimization tools in the design process of shaping rooms, walls and reflectors and how these methods can support creativity, accelerate solution finding, and interface with complex architectural ideas.

1 INTRODUCTION

Over the last three decades, the arsenal of tools used by acousticians to assist in the acoustical shaping of spaces has ranged from wave-based physical models to ray-tracing, wave-equation solver computer technologies, and fast physical prototyping technologies\textsuperscript{1}. Since then, computational tools have taken a dominant role in the architectural and acoustical practices. 3D computer modelling techniques have allowed the creation and acoustical analysis of complex shapes as seen in modern architecture designs.

To facilitate design, several modern modelling programs use geometries defined as mathematical functions such as NURBS. Invented in the 1960’s by Pierre Bézier and Paul de Casteljau for car manufacturers Renault and Citroën respectively, NURBS greatly facilitate creative designs by easily allowing the modification of a curvature’s geometry with sets of control points (knots), Figure 1. Subsequently, control points can also be assigned variables, which opens the door to prototype design parameterization and optimization.
This paper presents a series of case studies showing how computational design tools and optimization techniques can help support acoustical designers in room shaping. It addresses how such techniques can enhance the creative design process, accelerate solution findings and potentially lead to more deterministic design. The paper also presents how geometric modelling, optimization and auralization can be used together to design spaces or to achieve a particular sound signature\textsuperscript{2}. It concludes with perspectives for future design processes where computer-aided design tools such as real-time modelling and auralization tools can assist acoustical designers and allow in some ways to re-introduce the crafting of rooms in the design process as it could have existed in different periods of history.

\textbf{Figure 1:} Illustration of a spline and its control points (knots), and a NURBS extruded from the spline profile.

\section{FROM IN-SITU TO COMPUTATIONAL GEOMETRIC ACOUSTIC}

The shaping and carving of geometry for sound is not a new idea. There are countless examples of spaces shaped for sound which emerge across different civilizations and periods of history. As an example, for a new 750-seat opera house project being developed by the Constellation Center in Cambridge, Massachusetts, the author, along with the project’s principal Mr. Glenn A. Knickrehm, recently took inspirations from the Rokokotheater opera house in Schwetzingen Germany which reveals specific design detailing for sound.

Opened in 1752, there are records indicating that the architect (Nicolas de Pigage) may have used candle light on stage and mirrors in the audience area to observe light reflection patterns in order to shape the surfaces under the balconies and reflect sound for the audience underneath, \textbf{Figure 2 (left)}. Very much like the surface shaping which would be engineered today in computer models, Nicolas de Pigage may have realized one of the first examples of acoustical engineering. Recent acoustical analyses of the opera house\textsuperscript{3} have reported noticeable acoustical effects giving the subjective impression of singing voices filling the entire space.

For the new design which included a larger auditorium (Schwetzingen only sits 450), the original under-balcony element had to be scaled up to the new size, \textbf{Figure 2 (right)}. Modelled in Rhino3D, knot points were gradually pulled to create a range of NURBS profiles from which the entire under-balcony surface was drawn, \textbf{Figure 3}. Codes written in Grasshopper were used to trace rays in real-time and observe the reflection pattern of each geometry. The “Cage” function from Rhino3D was used to modify the NURBS surfaces for final tuning. Surfaces were then
exported into triangles and imported into CATT-Acoustic for prediction and final confirmation. Final design was chosen based on uniformity of coverage in the balconies.

This particular example illustrates how NURB surfaces are used to easily draw complex surfaces, analysed in real-time using ray-tracing, exported to acoustic simulation programs and designed to achieve the desired acoustical effect.

![Figure 2: View to the underside surfaces of the balconies in Schwetzingen opera house (left), view of the acoustic computer model of a new opera house design (right).](image)

![Figure 3: Spline profiles for the new shapes (top-left), “Cage” function allowing modification of knot point in groups (top-right), sound pressure level map (bottom-left), faceted NURB surface used for the final acoustical simulations (bottom-right).](image)

### 3 DESIGN OPTIMIZATION

While the previous example illustrates a non-automated form-finding process where the final design decision was obtained from iterative geometric changes, new developments in computational design are now incorporating theories of artificial intelligence and optimization algorithms which can automate and accelerate solution finding. Optimization algorithms are
used as solution search engines to explore and narrow a field of possible solutions. Some commonly used optimization algorithms include:

- Gradient-based methods with mathematical programming using the Karush-Kuhn-Tucker (KKT) conditions. These are often used for building structure optimization.

- Evolutionary algorithms: such as genetic, memetic, ant-colony, and particle swarm optimization techniques, based on pioneering work from John Holland. These are inspired by biological evolution such as selection, reproduction, mutation and recombination. Their aim is to efficiently exploit historical information to speculate on new search points with expected improved performance.

- Additional heuristic methods such as pattern search are used when the studied problem is not continuous and differentiable in the variables domain.

Applications to acoustics of such algorithms have been investigated through works by D. Rife, A. Blazejewski and T. Krzyzynski, T.J. Cox and P. D’Antonio.

A generalization of optimization algorithms for architectural acoustics can be summarized in Figure 4. A control interface (e.g. Matlab, Octave, Grasshopper, etc) sets the values of constrained variables (e.g. spline knot points, absorption, diffusion, transparency values, placement in space, etc). Changes are sent to an acoustic simulation computer model (e.g. CATT-Acoustic, Odeon, Grasshopper). Results are being compared to targets such as objective parameters, subjective criteria, or potentially a particular acoustical signature. Values of variables are then adjusted based on the learning of the optimization algorithm (Grasshopper algorithm, Matlab, etc). The results are stopped manually or automatically when results are converging towards an optimal solution.

**Figure 4:** Algorithm of computational design optimization adapted to architectural acoustics.
3.1 Optimizing Sound Projection for an Outdoor Acoustical Shell

This example illustrates how optimization algorithms have been used for the design of a portable orchestra shell to optimize both sound projection towards the audience area and the sound reflection back to the stage for performer support. The design led to the patented product, Sound Forms Plc\(^9\). At schematic stage, an initial profile was developed extending the shell over the stage to increase the sound coverage at further distance to the shell (Figure 5 bottom right). The internal face of the shell was then panelised to create cue-ball reflections for stage support. The facets of the internal shell were parameterized (Figure 5, bottom left) and optimization algorithms were used to refine the size and orientation of each facet to meet the acoustic goals but also the fabrication and constructability criteria. The targets for optimization were the following:

- Sound pressure level in the audience area.
- Support parameter ST1 on stage.
- Physical clearance between the panels and the external surface of the structure.
- Minimum space for integration of stage lighting.

The longitudinal profile was optimized automatically using the Galapagos genetic algorithm within Grasshopper and a bespoke ray-tracing script.

![Figure 5: Constructed acoustical shell (top-left), section showing acoustical shaping (top-right), initial study on surface panelisation (bottom-left), real time raytracing (Grasshopper) (bottom-right).](image-url)
Figure 6: SPL map with (top-left) and without (bottom-left) optimized acoustical shell, 10dB SPL attenuation contour range with and without the optimised shell (right).

3.2 Computational Study of Reflecting Surfaces in a Large Auditorium

In the design and renovation of the new 2,800-seat Northrop multi-purpose auditorium in Minnesota, both computational and optimization methods were employed to examine the shaping of various surfaces within the space.

Using NURBS surfaces and real-time parametric ray-tracing, the angles of the balcony fronts in the room were examined, in reference to the time delay from the direct sound. Rays were rendered showing time delay and attenuation with respect to the direct sound, using shapes and colors where the reflections cross the listening plane. In this way, the balconies were shaped in real time to avoid any reflections arriving 80ms after the direct sound.

Figure 7 – Parametric ray tracing using colors and shapes to characterize sound reflections, (top), real time shaping of balcony NURBS surfaces (bottom)
Additionally, optimization techniques were used together with fast computational ray-trace modeling in Radiance (lighting simulation software) to investigate the shaping of the front of the room. The objective of the calculation was to optimize the reflections of the overhead reflector to the audience area on the third balcony. The optimization was carried out using both pattern search and genetic algorithm scripts in MATLAB, maximizing the amount and uniformity of luminance (representing sound reflections) on the furthest audience plane in the room.

The overhead reflector was divided into multiple horizontal strips, each constrained to 90 degrees of rotational motion about the horizontal axis and connected from one to the other. The optimization routines swept through thousands of iterations of the overall reflector shaping, before converging on a solution after an average of 40 minutes, Figure 8.

![Figure 8: Frames from the design optimization sequence of the overhead reflector in the renovated auditorium design.](image)

### 3.3 Room Shape Optimization Based on a Target Acoustical Signature

In this example an acoustical signature is used as a target for finding a room shape solution. This approach was applied for a new recital hall project for the Tippet Rise Arts Centre project located in Montana. The new space uses as benchmarks famous chamber music historical precedents but also more recent spaces such as Wigmore Hall (London), Snape Maltings (Suffolk) and Sevenoaks (Sevenoaks) in England, both of which have a wooden pitch roof. The acoustics of the new space aspires to the envelopment quality of these spaces but for a smaller seat-count (200), while the architecture aspires to the feeling of a barn.

After having worked on the materials and the volume of the space, the design team decided to create an acoustic signature target that defines approximate intensity, timing, and incidence of reflections to emulate the envelopment qualities of the benchmark spaces while controlling loudness. The first reflections from the walls are softened by windows punch-outs and scattering effect (B and C). Reflections from the upper corners are maintained for envelopment (E). Direct ceiling reflections are softened (D) or re-directed towards the side walls for later lateral reflections (F).

The ceiling shape and the windows were parameterized in a computer model controlling placement, size, and shape. A total of 42 ceiling configurations were computed to calculate loudness indexes, reverberation time and impulse responses. For each configuration impulse
response plots were overlaid with the target acoustic signature according to their time and spatial distribution, and auralized in the ArupSoundLab © with anechoic music material.

**Figure 9:** Target acoustic signature and its primary reflections, position 2/3
d back in the Hall.

An intuitive guess for the shape of the ceiling would combine a variation of flat versus pitch ceiling elements to match the target impulse response. Results have confirmed this assumption. The best match was obtained for scenario 3, **Figure 10.** Modelling also helped determine the width of the flat perimeter of the ceiling versus the pitch section and the height of the each element.

**Figure 10:** Four ceiling examples from the 42 tested scenario and target acoustic signature.
4 CONCLUSION

This paper demonstrated that computational and optimization design tools are taking a stronger role in geometric acoustics. The examples presented in this paper showed that mathematically defined geometries can be easily manipulated and exchanged between modelling and analysis programs allowing for an easier shaping of rooms and surfaces. The process of digitally manipulating and crafting surfaces can be compared in many ways to sculpting real material or to the role of craftsman in architecture, as in the Schwetzingen opera house for example.

The paper also demonstrated the potential of optimization algorithms for geometric acoustics. Optimization helped the shaping of an orchestra shell to find the most adequate balance between reflected sound back to the stage and projected sound for the Sound Forms project, or deduce curvatures for the overhead reflector in the Northrop auditorium. By computing and testing hundreds of solution candidates, optimization algorithms can assist designer’s creativity and explore a wide range of possibilities to a given situation, narrow the field of possible solutions or create solution difficult to imagine. Such algorithms can also be used to check and confirm the validity of a particular design, and potentially aim towards more deterministic solutions, reducing risk of un-foreseen effects. Optimization along with parameterization of geometry also offers the possibility to use stylistic shapes, defined by architecture, to develop acoustical solutions within the visual vocabulary of a predefined architectural style, and to lead to more architecturally, integrated acoustical designs.

The possibility to sculpt spaces facilitates the creation of a particular reflection sequence or sound character. In the example of the Tippet Rise project, computational design tools coupled with auralization showed how the shaping of a room was obtained to match a particular impression of sound. It is also possible to imagine such techniques coupled with an auditory model, a set of subjective criteria or spatial parameters to optimize a design.

Work in the field of real-time visualization and auralization, such as the work conducted by the Gama Research Group at the North Carolina University, indicate that changes made in a computer model can be followed by real-time changes in an auralization. These developments along with the computational and optimization design tools lead to more intuitive and inter-active design tools, which ultimately give the ability for designers to shape spaces for a more holistic impression of sound.

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