Performative Design for Spatial Acoustics

Concept for an evolutionary design algorithm based on acoustics as design driver

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Abstract. The paper presents a performance-oriented design explorer tool focusing on finding spatial concepts based on acoustic parameters. The design explorer is a genetic evolutionary algorithm realizing evaluation through room acoustical and room morphological criteria. The paper describes the concept of the design system focusing on the synthesis of geometry, assignment of material properties, on the implementation of evaluation criteria and on the description of relevant acoustic criteria. The presented experimental algorithm is part of doctoral research work in progress. It marks a research milestone describing the concept and implementation of an evolutionary algorithm for spatial acoustics and presenting results produced by the proof of concept algorithm.

Keywords. performative design, room acoustics, evolutionary algorithm, design methodology.

INTRODUCTION

Performative Design is a design approach driven by performance-criteria of a spatial construct or building. The starting point of performative design is not the imagination of the final form, but a performance oriented understanding of requirements and capacities that the design should satisfy and unfold. The requirements and capacities may be defined as e.g. structural, environmental or acoustic criteria or other relevant criteria. The process can be focused on one of these requirements but it can also be based on a combination of different criteria. Consequently, a performative design explorer is a reverse mapping process of given or desired performance requirements towards a formal representation realised in geometry and materiality. The final design results from a bottom-up process entailing “[...] a transition from a design paradigm of “form making” to one of “form finding”” (Oxman 2008, p. 3). Thus the designer’s task changes to the design of a design system, which has the ability to explore an area of possible design results that satisfy the required performance criteria and unfold initially not entirely anticipated performance capacities.

EVOLUTIONARY DESIGN EXPLORER

The basic principle of an acoustic evolutionary design system is relatively simple. It is based on a repetitive process that creates geometry, assigns acoustic properties to the geometry, calculates the acoustic behaviour, evaluates the acoustic quality of
the created individuals, manipulates geometry and properties until acceptable results are produced. The design explorer is basically a twofold process. The geometry-synthesis-algorithm creates geometry based on a genetic code. The evaluation algorithm assigns quality values to each individual mainly based on acoustic criteria. Consequently, as a design is usually not generic but related to a specified design brief, the design explorer needs a description of the design task.

**DESIGN TASK (INPUT DATA)**

The starting point of a form evolution algorithm is the definition of a design task that should be solved by the algorithm. In the present case the design task can be described as the finding of an acoustically performative spatial envelope for a specific receiver-source configuration. The receiver-source configuration is a spatial configuration of sources that propagate sound and receivers that receive the propagated sound. This spatial receiver-source configuration can be understood as the desired spatial relation between spectators and the orchestra. It is regarded as the initial and crucial design specification which is defined by the designer and which is the main design decision besides the intended acoustic requirements. Figure 1 shows a model of the concert hall of the Philharmonie Berlin and the corresponding source (red) and receiver (green) configuration. The acoustic target values are based on the decision what type of acoustic room is intended. Due to research in the field of room acoustics (Fasold and Veres 2003; Barron 1993; Beranek 2004; Templeton 1993; Kuttruff 2004) accepted acoustic values for opera or concert halls or other acoustic purposes are published and will be described and listed below. In addition to these basic design decisions, specific contextual constraints are implemented, which are deduced from the particular nature of the given design task. It is obvious that the spectators, represented by the receivers, need to have an uninterrupted sight to the source and that the spectators should be located in the interior of the envelope. Another implicit constraint is the reduction of the envelope volume in order to satisfy basic spatial as well as economic criteria. Besides these implicit constraints and requirements a design task needs to be specified by morphological definitions. The explicit morphological definitions lead the design process from an universal search process, driven only by acoustical parameters, to a process also influenced by individual and intuitive design intentions. By defining and applying spatial morphological parameters as evaluation criteria to the design process the evolutionary design explorer takes the designer’s intentions into account. The alternative concept of direct user interaction through manual evaluation and selection is rejected because of the drawbacks like limited speed and efficiency of human evaluators or altering evaluation criteria (Duarte 2001, 13).
GEOMETRY SYNTHESIS ALGORITHM
The intention of the presented evolutionary design explorer is to provide a tool for finding spatial concepts with good acoustic performance. Thus the algorithm creating the geometry of the envelope has to be as universal as possible. The geometry created by the synthesis-algorithm should not be limited through structural preconditions. The synthesis-algorithm should be able to produce a wide range of different shapes.

Almost every shape can be approximated to a desired precision with simplicial complexes, which are mathematically defined as instances of a k-simplex (Attar et al. 2009). Almost every arbitrary surface, even if it is double curved, can be approximated with a grid of the 2-simplexes which we call triangles. A tetrahedron is also an instance of such a k-simplex, which means that every volume can be more or less approximated with tetrahedrons.

Figure 2
k-simplex shapes (Attar et al. 2009, p. 233)

Figure 3
Synthesis of polyhedron based on a simple point list.

Thus the geometry synthesis algorithm is using polyhedrons to form a spatial envelope. It transforms a given simple point list into polyhedrons. It is creating a polyhedron out of four points and is appending the following polyhedrons by using the next point and the nearest three points of the already existing object. Such a one dimensional and homogenous notation of geometry by a point list is very robust in regards to the implementation into a genetic evolutionary algorithm. Every gene can be handled with the same mutation parameters and can easily be recombined for crossbreeding at every point of the genome without regarding the fitting conditions of the geometry of the different parts.

The result of the synthesis algorithm is a watertight, not self-intersecting geometry, which can be generated from a genetic code consisting of a homogenous structure that is a point list. Even convex or concave structures can be generated in this way.
MATERIAL PROPERTIES ASSIGNMENT
In order to enable a subsequent analysis of acoustical performance, properties related to the acoustic behaviour have to be defined within the genetic code. The material related properties, which are relevant for acoustic performance, are the absorption value $\alpha$ and the scattering value $d$, both described as a value between 0 and 1. To preserve the homogeneous structure of the genetic code, every point is assigned with absorption and scattering value. Thus the genetic code is organized in groups where every group contains the point coordinates, the absorption value and the scattering value.

Due to the homogeneity of the genome the material properties are assigned to the points contained in the genome. However, for the acoustical analysis the properties must be assigned to the surfaces of the phenotype. Thus the synthesis algorithm transforms the point-related properties into surface-related properties. As a surface of the phenotype is represented by three points of the genotype, the corresponding absorption value of the phenotypic surface is generated from the assigned absorption value of these three points of the genotype. This can be realized [i] by the arithmetic mean of the points’ absorption values or [ii] by assignment of the maximum or minimum value of the three point base or [iii] by a random selection from the three point values. In empirical tests the different methods of absorption assignment have not shown any significant differences in the results.

EVALUATION ALGORITHM AND CRITERIA
The evaluation of the generated, individual phenotypes is a crucial aspect in an evolutionary algorithm. Based on the fitness ranking resulting from the evaluation process, individuals are selected for reproduction and thus provide the main input for the next generation. In most cases the fitness value is composed of several different evaluation criteria. In an evolutionary algorithm these different criteria are transformed into a single fitness value for each phenotypic individual. Formally the weighted quality value can be written as follows where $w * f(x)$ is the weighted evaluation function of a specified evaluation criterion:

$$f(x) = \frac{1}{\sum_{i} w_i} \sum_{i} w_i * f_i(x) | w_i, f_i \in \mathbb{R}_+ \{0 \leq w_i, f_i \leq 1\}$$

For the given design task of finding spatial concepts for enhanced acoustics, the evaluation criteria can be divided into two main groups: The first group includes acoustical criteria and the second one includes criteria relating to space morphologies. The acoustical criteria are well known and described in the scientific literature of spatial acoustics (Barron 1993; Beranek 2004; Kuttruff 2000), for example the desired reverberation time for concert halls is between 1.4 to 2.0 seconds. Besides the reverberation time other acoustic energy based criteria like early decay time, initial time, centre time or lateral fraction coefficient are relevant parameters. These parameters refer to the early and differentiated reflections in the related space and describe different energy ratios between direct sound energy and reflected sound energy.

These values are only available if a room acoustic simulation provides the energetic impulse response for the considered receiver positions.

Compared to acoustical criteria, criteria relating to space morphologies cannot be defined in such a relatively straightforward and quantifiable way. There are no universal definitions for space morphological criteria for concert halls, or indeed most other building typologies. Nevertheless, the authors

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|c|c|c|}
\hline
P0 & P1 & P2 & Pn \\
\hline
x0 & y0 & z0 & a0 & d0 & x1 & y1 & z1 & a1 & d1 & x2 & y2 & z2 & a2 & d2 & xn & yn & zn & an & dn \\
\hline
0.0 & 0.0 & 0.0 & 0.3 & 0.7 & 0.2 & 0.9 & 0.8 & 0.1 & 0.6 & 0.1 & 0.3 & 0.5 & 0.7 & 0.3 & 0.2 & 0.9 & 0.1 & 0.5 & 0.9 \\
\hline
\end{tabular}
\caption{Genetic code including absorption value $\alpha$ and diffusion value $d$}
\end{table}
are integrating morphological parameters into the evaluation algorithm that allow different types of geometry to be distinguished. Such as angles between surfaces, surface sizes, surface quantities, view axes, internal angles of surfaces, maximal or minimal volumes and many others. These criteria and their weighing in the evolutionary algorithm need to be defined by the designer based on project specific priorities and thus cannot be universally defined. For the current experimental proof-of-concept implementation the selected evaluation criteria are listed in the following table 2.

<table>
<thead>
<tr>
<th>criterion</th>
<th>characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>reverberation</td>
<td>acoustics</td>
</tr>
<tr>
<td>sight line prevention</td>
<td>morphological</td>
</tr>
<tr>
<td>min / max volume</td>
<td>morphological</td>
</tr>
<tr>
<td>receiver inside</td>
<td>morphological</td>
</tr>
<tr>
<td>surface angles</td>
<td>morphological</td>
</tr>
</tbody>
</table>

For the proof-of-concept the authors limited the acoustic evaluation parameter to the reverberation time in order to avoid time consuming calculations of room acoustic simulations. The presented algorithm investigates if the evolutionary algorithm works on an elementary level and if criteria which are related to spatial morphology are influencing the evolution of individuals.

**EXPERIMENTAL APPLICATION TO EXISTING SPATIAL CONFIGURATIONS**

The experimental set up of the above described genetic algorithm is representing a proof of concept and therefore it was required to reduce the amount of parameters to the relevant minimum.

The experiment investigates if the algorithm is capable to create valid spatial output based on a receiver-source configuration and if a receiver-source configuration is feasible as an input parameter to describe a design task. Thus the experimental application of the algorithm should show if the algorithm is able to evolve valid hulls based on the receiver-source configuration which are not self-intersecting, which provide sight-line prevention between receivers and sources, which enclose all receivers and sources and if the results are distinguishable related to the initial design task (receiver-source configuration).

The following figures show some results of the explorative design system described above. The receiver (green) and source (red) configurations are based on existing concert halls. These are the Semper Opera in Dresden and the Philharmonie in Berlin. The absorption value is represented by surface colour ascending from blue (0) to red (1). The evolutionary progress is mapped from the left to the right. The implicit side condition of sight line prevention, interior placement of source and receivers and an optimal reverberation time of 1.4 to 2.0 sec. are implemented in every series.

Without implementation of supplementary morphological conditions the evolution of the shape is negligible. The evolution process is focused on the adaption of material properties to achieve the required reverberation time.

If the morphological constraint of volume minimization is added to the evaluation algorithm the shape evolution becomes more differentiated even if the quality value approximates the maximum of 1.

The experimental set-up demonstrates a tendency of the evolutionary algorithm to prioritize the ‘optimisation’ of the absorption value over geometric adaption. The convergence of absorption values during the evolutionary form generation process is plotted in figure 8. The absorption value decreases very quickly from a high level to nearly 0. Regarding the reverberation formula, which is expressed as a specified ratio of Volume to equivalent absorption surface, one possible interpretation is that the created volumes remain too big. In other words, with the given parameters the algorithm is not capable to shrink the shape significantly without violating the sight line prevention side condition. Thus it is more efficient to adapt absorption values of the surfaces.
Semper Opera, Dresden

Figure 4
Left: frame 200, q=0.70.
Middle: frame 2500, q=0.73.
Right: frame 7300, q=1.0

Philharmonie, Berlin

Figure 5
Left: frame 200, q=0.74.
Middle: frame 3000, q=0.74.
Right: frame 4600, q=0.74.

Additional side condition:
minimize V to 0.1 x max. volume.

Figure 6
Left: frame 200, q=0.82.
Middle: frame 3000, q=0.82.
Right: frame 7000, q=0.99.
Additional side condition:
minimize V to 0.1 x max. volume.

Figure 7
Left: frame 200, q=0.83.
Middle: frame 3000, q=0.83.
Right: frame 9500, q=0.97.
Additional side condition:
minimize V to 0.01 x max. volume.
The test series also demonstrates that increasing optimisation pressure through the integration of the minimisation of the volume as evaluation criteria has a significant influence on the results. In the first two series, the geometry hardly changes. However, in the following series the individual geometries differ all the more once the target value for the desired volume is decreased. Side conditions as sight line prevention, which are integrated as soft conditions into the fitness function, are also achieved and provide additionally optimisation pressure.

The side conditions like sight line prevention or maximal volume size are integrated as soft constraints. They are implemented as evaluation criteria into the evaluation algorithm. Due to this implementation method individuals can ‘survive’ even if constraints are violated. Thus the selection process is more tolerant and provides a bigger scope for evolution.

**CONCLUSION**

The presented evolutionary algorithm is composed of a geometry synthesis algorithm and an evaluation algorithm. The geometry synthesis algorithm was able to create valid shapes with the assignment of individual acoustic properties based on the described initial source-receiver configuration. As a consequence the definition of the source-receiver configuration is regarded as a valid input data for the design system. The source-receiver configuration, which is the representation of the design brief, offers the possibility to define tasks which differ from known spatial concepts that still mainly refer to traditional musical presentation format. Regarding the results of different source-receiver configurations one can state that the created shapes are not arbitrary but refer to the initial definition of the design task. Thus it provides the potential to explore new design concepts for acoustical spaces.

The point list used for encoding geometric and material properties proofed to be a universal and efficient notation in the context of the proposed genetic evolutionary algorithm. The implementation of morphologic side conditions has a positive influence on the evolutionary process. The morphological side conditions are capable of increasing the fitness pressure. The implemented geometric criteria, which are sight line prevention and volume minimisation, are relevant and valid parameters for a form evolution process for acoustical spaces. The influence of space-morphological criteria is significant and dominant at this stage because more differentiated acoustical simulation results are missing.

Future research should aim for the description of additional space-morphological criteria which are eligible to influence the shape evolution towards intuitive design intention. The integration of geometry related acoustic criteria by implementing a room acoustical simulation into the evaluation algorithm is intended and holds the potential to significantly improve the design system.
REFERENCE