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Rapid 3D Auralization Of Historically Significant Buildings For Immersive Classroom Activities

Jonas Braasch[(1)], Samuel R.V. Chabot[(2)], M. Jerry Huang[(3)], E.K. Ellington Scott[(4)]

[(1)]Rensselaer Polytechnic Institute, Troy, USA, braasj@rpi.edu
[(2)]Rensselaer Polytechnic Institute, Troy, USA, chabos2@rpi.edu
[(3)]Rensselaer Polytechnic Institute, Troy, USA, huangm5@rpi.edu
[(4)]Rensselaer Polytechnic Institute, Troy, USA, scotte3@rpi.edu

ABSTRACT

This paper proposes an efficient method to create auralizations of acoustical landmarks using a 2D ray-tracing algorithm and publicly available floor plans for a 128-channel wave field synthesis (WFS) system with 2.5D approximation. Late reverberation parameters are calculated using additional volumetric data. The approach allows students to create auralizations from floorplans and other available information (e.g., building height, material info, and acoustical parameters) using Matlab or Octave. By using adequate sound sources, important historical events can be recreated. The listeners can walk through these recreations over an extended user area, such as an immersive classroom, and the software suite can be used to calculate room acoustical parameters for various positions directly using a binaural rendering method or via the WFS simulation.

Keywords: Virtual Acoustics, Wave Field Synthesis, Raytracing

1 INTRODUCTION

The paper presented here aims to create walkable room simulations using a rapid prototyping approach. Using a 2D ray-tracing algorithm, the program can render sound fields over an extended listening area for classroom activities. The program is used regularly in a class titled *Aural Architecture*, where students create their own final projects. The program can also render binaural impulse responses using Head-related Transfer Functions (HRTFs) for the automated analysis of acoustical parameters using binaural models [3]. The concept uses a 2D method to render the direct sound signals and early reflections, a feasible approach considering that wave field synthesis (WFS) systems are usually 2D setups, where loudspeakers are placed along the perimeter of an extended listener area [4]. The proposed method is compatible with the 2.5D operator for WFS.

The system is primarily used to recreate historic architectural venues from antiquity to today so that listeners can experience these venues' acoustical footprints over the extended floor area (10×12 sqm) of Rensselaer's *Collaborative Research Augmented Immersive Virtual Environment Laboratory* (CRAIVE-Lab). The CRAIVE-Lab uses 134 full-range loudspeakers (JBL 308, 128 speakers along the lab's perimeter at ear height, plus six ceiling speakers). Eight short-throw front projectors reproduce congruent immersive 360-deg images, e.g., HDR panoramic photos, on a screen that encloses the listening area up to a height of 4.3 m. The screen is microperforated for improved acoustic performance. This makes the CRAIVE-Lab a unique venue for auralizations, given that typical CAVE systems have hard projection surfaces. The latter create audible room reflections that superimpose with the simulated room reflections of the WFS signals. The floor area of the CRAIVE-Lab is also more extensive than that of a typical CAVE. The lab can host up to 49 participants at a time (restricted by fire code), providing the opportunity to experience an extended section of the simulated acoustical enclosure. The lab has been optimized for user interaction with the panorama-screen environment [5].

The proposed auralization method allows users to render historic buildings from scaled floor plans, which are often publicly available in contrast to full three-dimensional CAD models. The research started from an

Figure 1. Photographic panorama presentation of a marketplace (Weikersheim, Germany) in the CRAIVE-Lab.

educational angle, and much of the description in this paper still reflects this original goal.

The 2D approach has some educational advantages over traditional 3D methods. Firstly, it allows creating a model in less than an hour to a few hours, given the complexity of the floor plan and additional volumetric estimations. A 3D model typically takes much more time to reconstruct, and often the necessary information is not available. The rendering process is also much quicker, and it allows students to render a 128-channel simulation in class, while a 3D method takes much longer for the same number of channels. Given that the CRAIVE-Lab and most other WFS systems position all loudspeakers on a 2D plane, the compromises of the dimensional reduction are acceptable, as long as the volume of the enclosure is considered to calculate the parameters for the late reverberation. For three-dimensional loudspeaker setups, e.g., dome configurations for higher-order ambisonics, the 2D approach has more setbacks, although the annotated floorplan approach might still be useful for educational purposes. The biggest side effect of dome configuration will be the lack of ceiling reflections, which have been deemed important in concert-hall acoustics. For these setups, it might be useful to estimate and add at least one first-order ceiling reflection, for example, using another 2D approach in the vertical plane that dissects a concert hall from front to back.

In the next section, the basic concept of our proposed auralization technique is discussed, followed by auralization examples that are described in Section 2. The paper concludes with a brief conclusion section.

2 METHODS AND IMPLEMENTATION

Figure 2 shows the system architecture of the ray-tracing program. All input variables and data are shown at the bottom. The basis for auralizing a building or outdoor venue is a floor plan with a scale or known dimensions. Further, a wall and floor materials database is utilized to determine absorption coefficients [7]. The user determines the locations of sound sources and receivers and provides sufficiently anechoic sound files for auralization. The receiver positions determine the locations of virtual microphones for the WFS loudspeaker locations, the location of a virtual dummy head (rendered through head-related transfer functions), or the position of a virtual spherical microphone array.

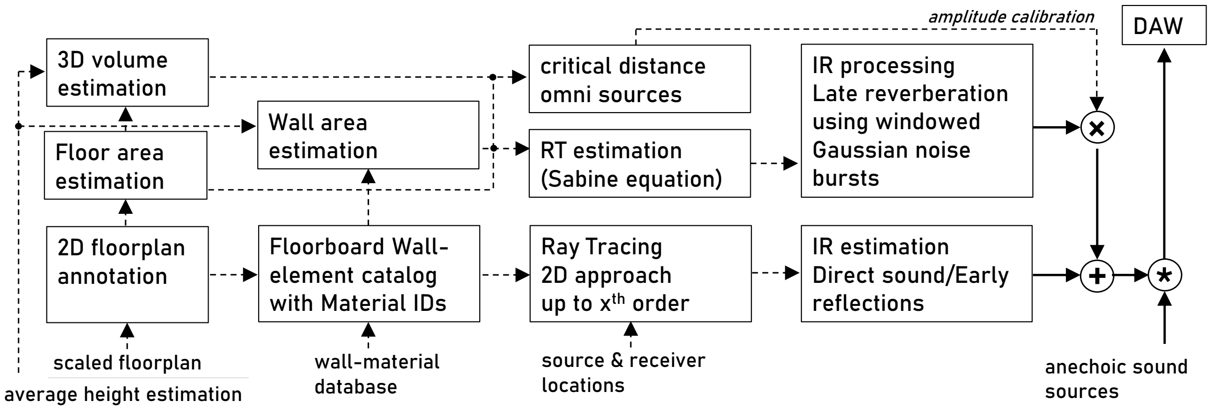

Figure 2. System architecture for the auralization algorithm.

2.1 Floor-plan annotation

In order to allow fast calculations, the method presented here is confined to simulations in the horizontal plane (two-dimensional rendering method). This allows for the simulation of complete walk-throughs using a batch process. The ray-tracing algorithm was implemented in Matlab following common practices [14, 9, 2]. Additional features were added where needed, for example, an algorithm to create circular boundaries to simulate tree trunks and a method to rapidly generate models from floor plans.

Coordinates of acoustic boundaries can be assigned to the ray-tracing algorithm in three different ways: (i) line segments with start and end points representing walls, (ii) squared pillars with the center coordinates and the pillar width, (iii) circles represented by center and radius coordinates. Figure 3 shows an example of the ray-tracing software for a concert hall in Eisenstadt that was recreated from an annotated floor plan. For this purpose, publicly-available floor plans are marked up in a standard bitmap editor (GIMP, Photoshop, etc.). Red dots are used for room corners, green dots for squared pillars, and blue dots for circles – see Fig. 3, left graph. In the next step, the program plots annotated points on top of the map providing a unique index for each annotated point – see Fig. 3, center graph. The user then creates a list of how the red points connect to walls. The scale of the floor plan needs to be annotated, and the original dimensions need to be handed over to the program (e.g., 1 and 10 m for two scale points). The program then transforms these data points into an editable list of geometrical objects that can be extended by a user, for example, by adding identifiers for wall materials. The user corrects and edits these pairs to finalize the digitized floor plan.

The user can either assign a single wall-material ID to all walls or specify individual wall-material IDs for each wall – see Fig. 2, bottom, 2nd-from-left box. Currently, wall material data is taken from a DIN database, and the database contains a short description of the material, frequency-specific absorption coefficients, and Finite-Impulse-Response (FIR) filter coefficients. The latter is needed to compute adequate room impulse responses.

2.2 Ray-tracing algorithm

For each sound-source position, the program sends out rays at equidistant azimuth angles covering the full horizontal plane (360° circle) – see Fig. 2, 3rd-left bottom box. Intersection points are computed for each ray and boundary object using the solution of the line–line intersection problem in Euclidean geometry. For each ray, the closest boundary intersection is determined. At the intersections, the reflection angle is calculated using Ibn Sahl/Snell's law [12, 15]. Then the next-order ray is sent out into the new direction until the maximum order (e.g., the number of reflections) specified by the user is reached or the ray exits the floor plan – see Fig. 4. The outgoing rays are stored as a sequence of ray elements containing the intersection points and the boundary material identifiers. Since the initial angles are stored with the rays, a source-specific directivity pattern can be simulated after all rays have been traced.

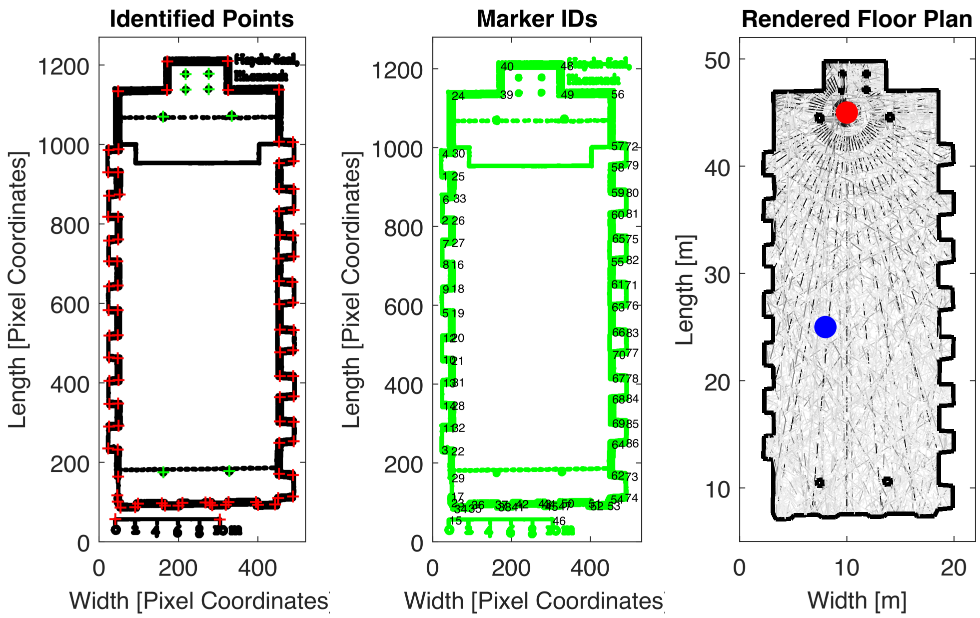

Figure 3. Demonstration of the ray-tracing algorithm for the Haydn-Saal in Eisenstadt, where Joseph Haydn was active. **Left:** Processed marked-up floor plan for visual inspection, **Center:** Assignment of wall-corner identification numbers, **Right:** Geometric model with a sound source (red dot) and receiver (blue dot) and calculated rays. The original floor plan was obtained from [10, p. 147].

2.2.1 Creating a room impulse response

In the following step, the rays are collected by receivers in the module *IR estimation* – see Fig. 2, rightmost bottom box. Receivers can be located anywhere in the rendered room. For WFS, a virtual array is placed into the floor plan section that should be auralized. The receivers (virtual microphones) are positioned at the WFS loudspeaker positions. So for a 128-channel loudspeaker system, the same number of receivers are placed at the loudspeaker positions. For each receiver, a separate impulse response is created. A virtual circle with an adjustable diameter is positioned at each receiver location to catch the rays. Then, the algorithm calculates which ray elements intersect the circle, and for all positive cases, the total ray distance between sound source and receiver is calculated. All listed values are stored together with the final angle of incidence, the angle the ray was initially sent out, the reflection order, and the sequence of wall identifiers. Based on these data, the impulse response is created. The direct sound and reflections are computed as delta peaks at the delays that correspond to the ray's path length from the source to the receiver. In addition, each impulse is transformed the following way:

1. The intensity of the ray is reduced based on the inverse-square law. Consequently, the sound pressure magnitude decreases with $1/r$.

2. The high frequencies are filtered out based on atmospheric attenuation.

3. The absorption effects of the walls and other boundaries are simulated using a cascaded Finite Impulse Response (FIR) filter. The material-specific filters are chosen from a DIN database [7]. The number of cascaded filters matches the order of the reflection.

4. In the final step, direct incoming sound and reflections are selected by their close proximity passing a receiver position within the virtual circle that was placed around it. The virtual receivers are directionally sensitive using the positive lobe of a figure-of-eight pattern. The latter point outward the array to avoid

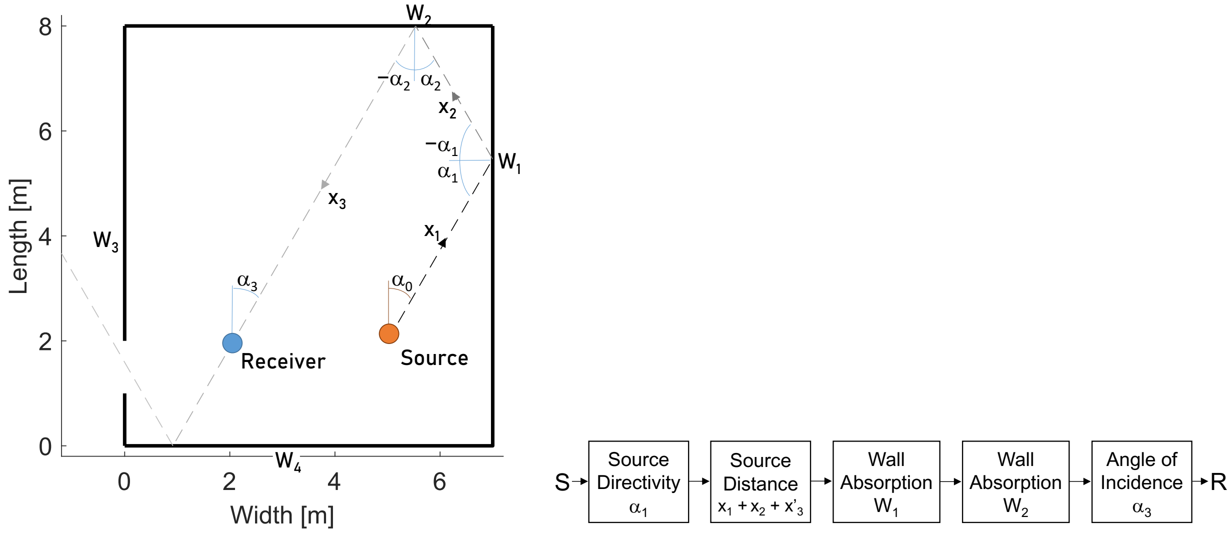

Figure 4. Left: Example of a ray-tracing pathway, Right: Ray-tracing signal flow diagram for this pathway.

echo artifacts resulting from rays passing through the array at the opposite end of the array. An overlap-add method ensures that the delayed reflections can partially overlap, which can happen because of the cascading FIR filters' prolonged effect that simulates the wall reflections.

2.2.2 Simulation of late reverberation

Late diffuse reverberation is computed in addition to the early reflections generated by the ray-tracing model. The structure of the simulated reverb tail is constructed from a Gaussian noise sample with temporal windowing to simulate the reverberation decay – for details, see [4]. This method reflects that the late reverberation tail is formed by a stochastic process with an underlying Gaussian distribution.

3 AURALIZATION CASE STUDIES

This paper aimed to test the feasibility of the rapid prototyping approach. For this purpose, several landmark buildings were selected to see if a single person could model them within one afternoon, a typical time slot available for preparing a class, such as in this case "Aural Architecture."

3.1 Notre-Dame of Paris

The first building selected was the *Notre Dame* cathedral in Paris. Built between the years 1163–1260, the church is among the most notable examples of Gothic church architecture. Moreover, large cathedrals likely had a crucial role in the development of polyphonic music, a musical movement spearheaded by medieval composers Léonin (1135–1201) and Perotin (1160–1230), who were both based in Notre Dame. One theory states that polyphonic music was a consequence of the long reverberation found at large churches. The reverberation tail of approximately 6 seconds [11] prolongs a sung note to the extent that multiple sequentially sung notes will overlap in time, leading to the idea of having three voices sing these accidentally overlapping tones simultaneously. It should be noted, though, that Léonin and Perotin's work preceded the completion of Notre Dame. The polyphonic movement is also closely tied to the development of music notation in part because it was difficult to remember each voice, especially the center line, which completes the chord structure and is typically not very memorable by itself.

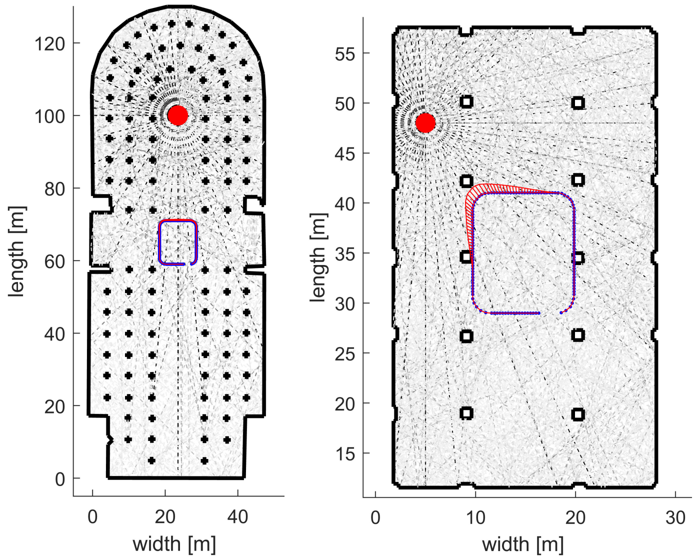

Figure 5. Floor plans of two landmark buildings created using the rapid-prototyping approach – left: Notre-Dame (Paris), right: Westerkerk (Amsterdam). The blue rounded rectangle represents the CRAIVE-Lab's spatial footprint in 2D, while the red dots represent source position, and the connected red lines represent sensitivity among all secondary sound sources (individual loudspeaker).

Name	Length	Width	Height	Volume	No. seats	RT
First Gewandhaus	23 m	13 m	7.5 m	2,242.5 m^3	400	1.3 s
Second Gewandhaus	38 m	18 m	15.5	11,200 m^3	1,560	1.6 s
Third Gewandhaus	32.3 m	36 m	19.8 m	21,000 m^3	1,900	2.0 s

Table 1. Dimensions for the three Gewandhaus concert halls (RT stands for reverberation time).

3.2 Westerkerk in Amsterdam

The second selected building is the Wester Church (Westerkerk) in Amsterdam, the largest protestant church in the Netherlands. Hendrick de Keyser designed the church, which was built during the years 1620–1631. The Renaissance church has an 85-m tall tower, a historic pipe organ from 1686, and is the burial site of Rembrandt van Rijn. For this building, it is essential to remember that the church Reformation also had profound acoustical consequences. By empowering ordinary citizens, it became necessary that everyone could follow the church service, and local languages replaced Latin, which was only understood by a small part of the population. In 1708, Christopher Wren, who was commissioned to build 50 new churches, determined that the new churches needed to be sufficiently small so everyone could follow what was being said by the preacher [6], [8, Page 9]. The produced floor plan exhibits how small the Wersterkerk is compared to Notre Dame. Here, the plotted dimensions of our WFS array showed to be a valuable tool for grasping the overall scale of a building.

3.3 Gewandhaus in Leipzig

The acoustics and history of the Gewandhaus Orchestra is an ideal example of aural architecture in the immersive classroom. The Gewandhaus Orchestra is the first German orchestra formed by a civil movement and not as part of court procedures. It started in 1743 under the label "Great Concerts" [Grosses Concert]. The Gewandhausorchester was initially a small ensemble of 16 musicians, which grew over time to the size of a full late-romantic orchestra with 185 full-time musicians. Over time, the orchestra has been housed in different buildings, reflecting the modern concert hall's evolution. After performing for years in a regular tavern named

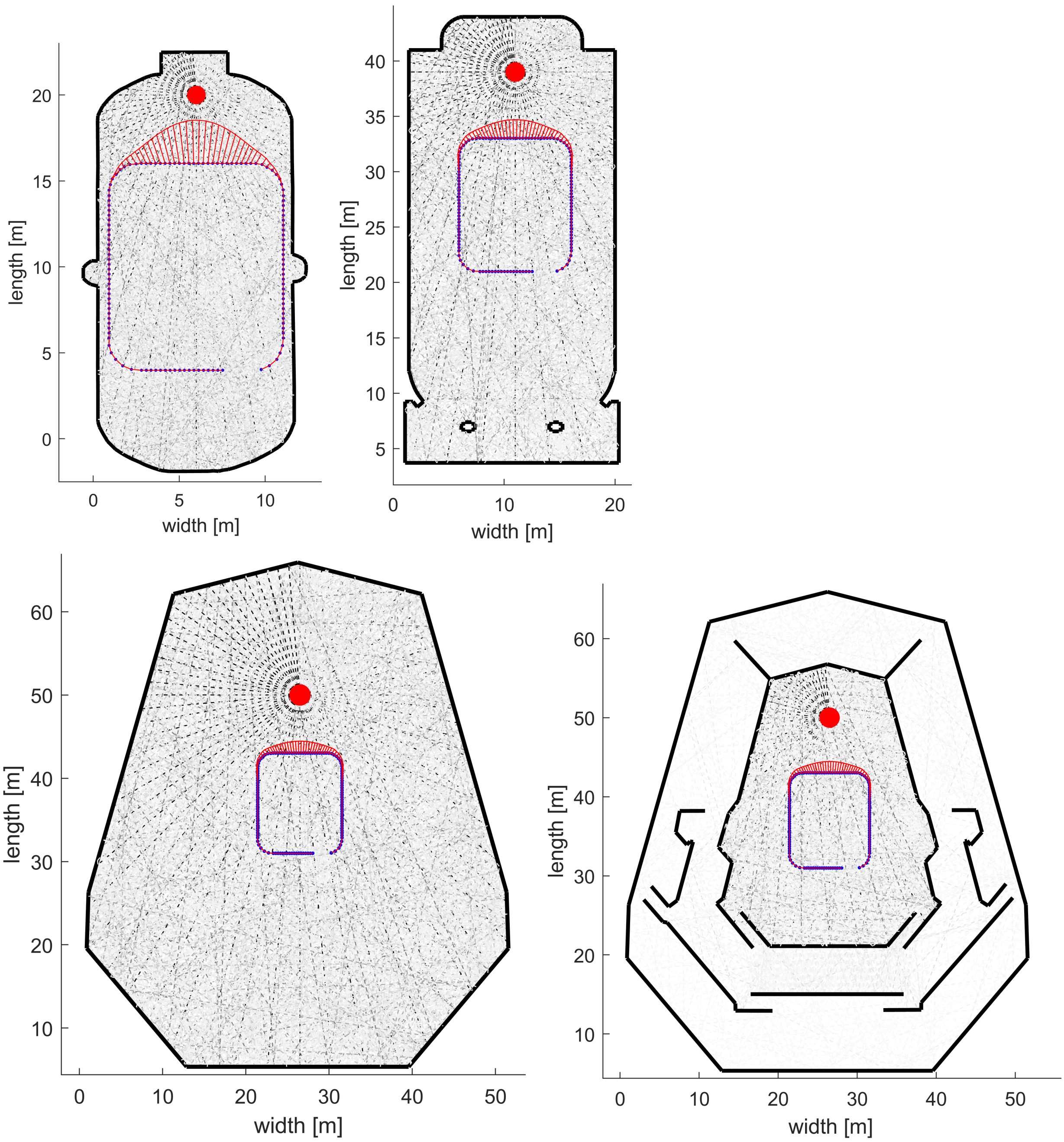

Figure 6. Simulated sound fields for the three Gewandhaus concert halls: First Gewandhaus (top-left panel), Second Gewandhaus (top-right panel), Third Gewandhaus for overall structure (bottom-left panel), Third Gewandhaus for effective early reflection surfaces (bottom-right panel).

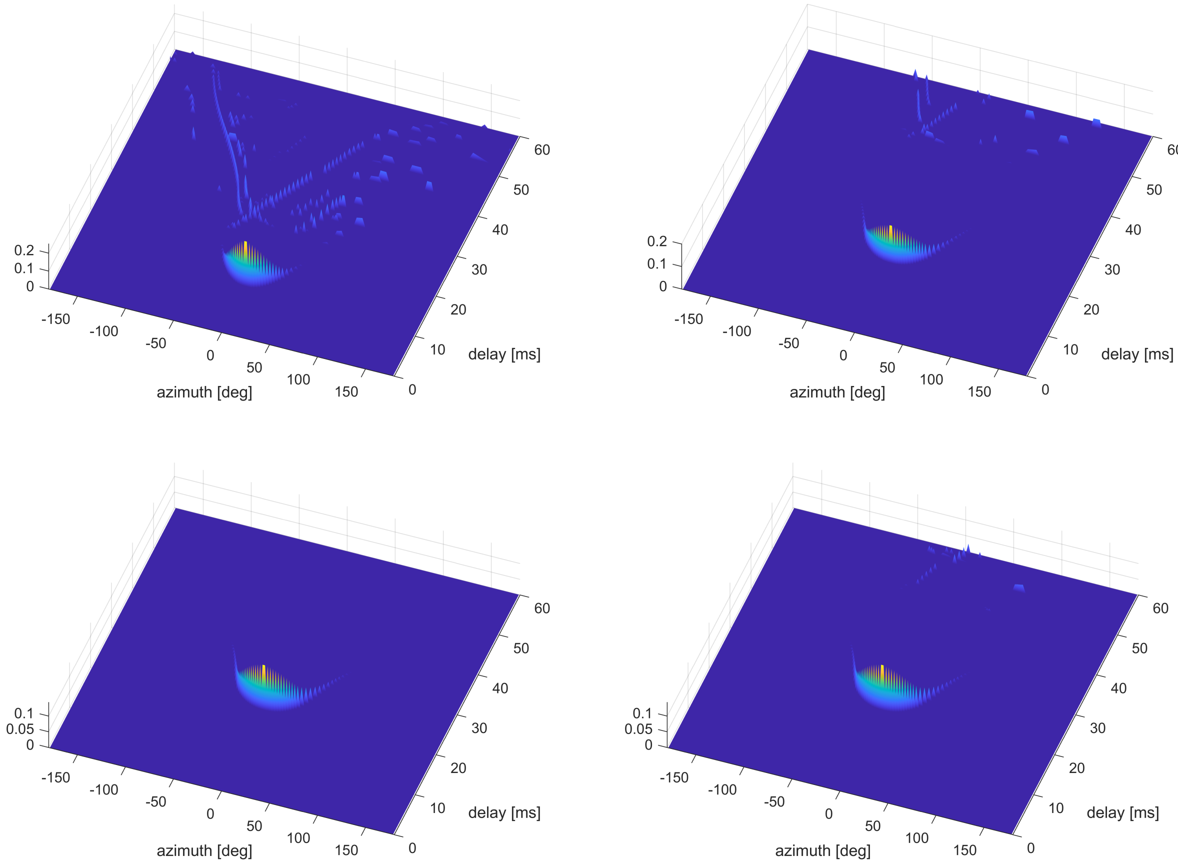

Figure 7. Simulated 128-channel impulse responses for the three Gewandhaus concert halls: First Gewandhaus (top-left panel), Second Gewandhaus (top-right panel), Third Gewandhaus for overall structure (bottom-left panel), Third Gewandhaus for effective early reflection surfaces (bottom-right panel). Each graph shows the spatially aligned impulse responses for the CRAIVE-Lab configuration.

Zu den drey Schwanen [at the three swans], a dedicated concert hall was integrated into a former garment trading building. The hall was constructed in 1781 by Johann Carl Friedrich Dauthe. This hall is known as the first Gewandhaus.

The floor-plan-based auralization process presented in this article is ideal for simulating the first Gewandhaus, as there is little data on this building; it was demolished before architectural acoustical design principles were developed. The first Gewandhaus resembles the transition from court-based orchestral practices to private organizations. Given their transitional nature, these provisional solutions have been replaced by specifically designed concert halls, and floor plans, drawings, and verbal descriptions are the only evidence of these buildings. These circumstances make it an ideal project for the proposed rapid prototyping method. The simulated sound field shown in the top-left panel of Fig. 6 was created using an existing floor plan. The height of the building can be estimated from contemporary drawings. The second Gewandhaus was designed by Martin Gropius and completed in 1884. It was destroyed in World War II. After a transitional period with a repurposed building (*Kongreßhalle am Zoo*), the current Gewandhaus opened in 1981 and was the only single-purpose concert hall erected by the East German Government. Table 1 lists the dimensions for all three Gewandhaus concert halls – the data for the other two concert halls and the seat counts have been described in the literature – e.g., see [13, 1].

Various sources list measured or estimated reverberation times for all three halls, including data for the second Gewandhaus that Clement Sabine analyzed in a case study while planning the New Boston Music Hall. The top-right panel in Fig. 6 depicts the simulated sound field for the second Gewandhaus. Note that the dimensions are much larger than the first hall, with a seating capacity that is about four times as high and a volume that is about five times larger. The plotted location of the simulated wave field synthesis array in both venues provides a good reference for the scale. The current fan/rhombus-shaped concert hall has much larger dimensions than its two predecessors – see Fig. 6, panel bottom left. However, when computing the reflecting walls at the concert podium level, the effective reflecting walls are much closer to each other, which is a strategic part of the acoustic design. Now the effective floor area is similar to that of the second Gewandhaus – see Fig. 6, panel bottom right.

Figure 7 shows the simulated impulse responses for the four simulated sound fields from Fig. 6. Given its small dimensions, the early reflections arrive the earliest for the First Gewandhaus and are noticeable later for the Second Gewandhaus. For the Third Gewandhaus, early reflections are absent in the graph if the outer enclosure is used for the simulation, but they are present if the inner enclosure is simulated as well. In the latter case, the strength of the reflections is similar to the second Gewandhaus simulation.

The growing library of simulated venues also includes the Cologne Cathedral, Savoy Ballroom Jazz Club, Columbia 30^{th} Street Studio, St. Mark's Cathedral in Venice, St. Patrick's Cathedral in New York City, Pantheon in Rome, Amphitheatre in Trier, to name a few.

4 CONCLUSION

A rapid auralization method was demonstrated in this paper. The process allows rapid prototyping of acoustical enclosures using annotated floor plans and a ray-tracing method. It usually takes less than an hour to annotate the floor plan for a project and about another hour to render the impulse responses and create the auralizations for a brief demo with eight sound sources and 128 loudspeakers on a typical desktop computer.

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