Room acoustic 3D models from automatically meshed point clouds

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1. Introduction

1.1. Background and motivation

Obtaining three-dimensional models of existing architectural spaces for acoustic simulation presents significant challenges, particularly when starting from data acquired through mass capture techniques. Manual modeling based on such datasets or alternative sources is typically a time-consuming process, does not allow direct validation of the geometry accuracy, and introduces dependency on the operator's subjective modelling skills (Berkeley et al. (2014)). The resulting topology, preservation of details, and subjective views on their relevance substantially influence the results of the acoustic simulation (Siltanen et al. (2008)). Additionally, the need for corrections—or even the complete remodeling of geometries—is usually identified during or after acoustic calculations, compelling a repetition of the entire modeling process and thereby reintroducing the aforementioned vulnerabilities.

The primary objective of this paper is to provide a methodology which transfers massive data capture 3D models into precise simplified geometric models for room acoustic simulations. For this, the effects of the geometry simplification parameters are evaluated on two aspects: the accuracy of the simplified mesh and their effect on simulated room acoustic parameters.

1.2. State of the art and contribution of this work

3D building models have been used in acoustic simulations since the application of computers to the theory of geometrical acoustics. Manfred Schröder's work at Graham Bell's laboratory from 1961 is traditionally given as the birth date of sound simulation. Following those steps, the initial Ray-tracing algorithms computing room acoustics, concert hall acoustics and auditoriums were investigated for home musical reproduction systems, or to adapt concert hall features for without changing the architecture (Schroederf and Logan (1961); Vorländer (2020)). During the quest of acoustic plausibility of acoustic simulations, more complex room modelling approaches were introduced. The geometrical modelling approaches of Kuttruff and Cremer were developed. In particular, the work of Michael Vorländer during the last decades has delivered evidence on the geometrical level of detail, the absorption and scattering properties of materials and the impact of them on the quality of the acoustic simulations (Summers (2008); Vorländer (2020)). In the industry, those modelling theories were transferred to software applications, such as ODEON, CATTAcoustics, Treble, among others. On the academic side, several open-source software for room acoustics simulation is used, such as RAVEN or Tascar.

Computational acoustic simulation has traditionally required manually generated conventional CAD models. Manual modeling from point clouds is time-consuming and presents difficulties in direct geometric validation. It also generates a strong dependency on the modeler's skill, while preventing replication under different circumstances, spaces, and times. Topology, detail preservation, and the subjective evaluation of which elements are relevant to model significantly affect acoustic results. Moreover, the need to correct or even completely redo the modeling often becomes evident during or at the end of the acoustic calculation, forcing the process to be repeated with no guarantee of avoiding the aforementioned vulnerabilities. The acquisition of measurements and geometries has been the subject of numerous studies, and advances in massive data capture technologies such as photogrammetry and terrestrial laser scanning (TLS) have contributed to obtaining precise measurements. Nevertheless, the automated generation and use of three-dimensional models of existing architectural spaces has not yet proved convenient for the purpose of simulating their acoustic behavior. These methodologies have primarily focused on reducing the number of faces in order to lower computational load, but they encounter difficulties, especially when the data originate from massive capture processes (Llorca-Bofí et al. (2022)). Several authors have contributed in methods for calibrating the simplified models (Pilch (2020)), approaches to simplify the geometries (Siltanen et al. (2008))

The purpose of the proposed methodology is to ensure suitability in both scenarios, so that it can operate with data from any massive capture system. The aim is for any point cloud—whether ordered or unordered, raw or processed—to be usable for the description, simplification, and three-dimensional meshing of architectural spaces. The capture technologies employed in this study—modern terrestrial laser scanning (TLS) and photogrammetry—present their own strengths and limitations. Laser scanning is characterized by high metric precision, achieving millimetric accuracy, and by its robustness to noise. Its main drawback, however, lies in the considerable workload it requires and its strong vulnerability to occlusions, which create shadows and data gaps, thereby compromising model continuity and point density. Photogrammetry, in contrast, produces noisier results but offers more homogeneous coverage if the capture is properly executed, while also reducing occlusion-related issues thanks to the flexibility of handheld cameras. Nonetheless, it lacks scale and is prone to deformations, requiring external control points to fix scale and position. In recent years, the trend has been toward combining both technologies, integrating the geometric accuracy of laser scanning with the chromatic reliability and spatial continuity of photogrammetry. Software such as Pix4D, Metashape, or RealityScan operate under this logic in spatial and architectural reconstruction, as they allow simultaneous processing of TLS and photogrammetry data.

2. Study Cases

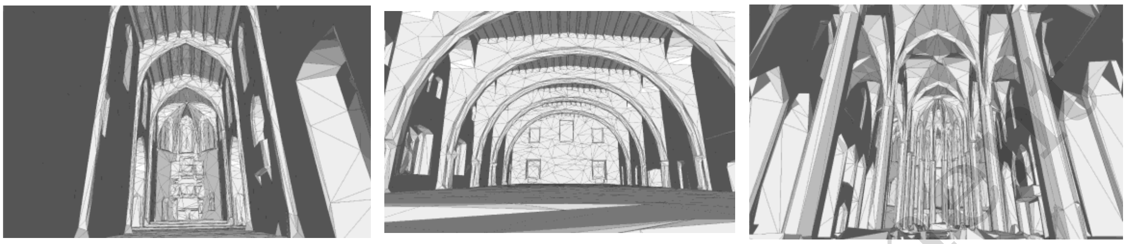

Figure 1: 3d Mesh 10k Faces, Left Saló del Tinell. Middle: Saló del Tinell. Right: Santa Maria del Mar.

2.1. Chapel of Santa Àgata

The Chapel of Santa Àgata is a building belonging to the Gothic reform of the Palau Major in Barcelona, Spain. The building was completed in 1323 after more than two decades of construction. The resulting space is a nave 29 meters long and 6.5 meters wide. The space is organized as a rectangular nave with a polygonal apse covered by a ribbed vault, while the nave adopts a gabled roof supported by pointed arches resting on pilasters and lateral walls with embedded buttresses. The chapel also contains lateral chapels that were added at a later stage. It is a compact space with thick masonry walls and a unified interior.

2.2. Saló del Tinell

The Saló del Tinell was the great ceremonial hall of the Palau Reial Major. Its construction was carried out between 1359 and 1370. It is one of the purest examples of a large representative Gothic hall in the Iberian Peninsula. The rectangular plan is covered by six semicircular diaphragm arches that articulate the space into six bays, topped by a wooden gabled roof that allows the achievement of large spans with economical use of material and a sense of openness consistent with its ceremonial function and symbolic representation of power.

2.3. Basilica of Santa Maria del Mar

The Basilica of Santa Maria del Mar is the paradigm of Catalan civic Gothic applied to religious architecture. It has a basilical plan with three naves of equal height, generating a continuous and unified spatial experience. The side aisles are defined by slender octagonal pillars that also delineate the central nave. The intercolumniation is approximately 13 meters, producing a spacious and uninterrupted interior throughout the basilica.

In our dataset for Santa Maria del Mar, the survey corresponds to an unordered point cloud without normals, resulting from post-processing of a capture campaign conducted between 2006 and 2008 by the VIMAC laboratory of the UPC. Nevertheless, the spatial complexity of the building and the scale of the survey make this model a valuable example for demonstrating the methodology's capacity in large-scale heritage contexts with incomplete records. Additionally, acoustic data for the Basilica were retrieved from previous study (Villarreal Godoy (2023). Thus, the implemented T30 values for this space are: 10.66s (100Hz), 8.94s (500Hz), 2.49s (5000Hz).

Meshing methodology

Our methodology, which falls outside the scope of this paper, is described in the flowchart shown in Figure 2. It consists of three main phases. The first phase involves meshing through Poisson Reconstruction or Iterative Poisson Reconstruction when the original data do not contain orientation information (normals), resulting in a closed mesh. Secondly, Alpha Reconstruction ensures the correct topology of the mesh, and finally, iterative downsampling guarantees the progressive reduction of faces in stages so as not to lose the conditions established in the first two phases and to ensure the suitability of the output mesh.

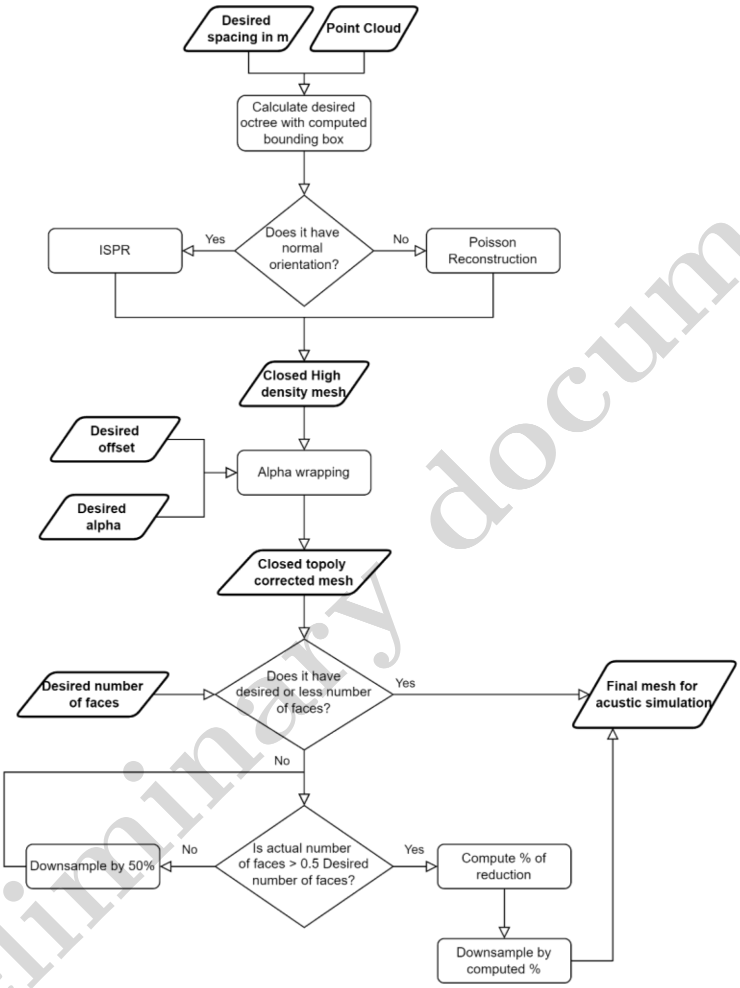

Figure 2: Flow diagram of the applied methodology

4. Simulation of room acoustic parameters

After the geometrical considerations above, three simplification models per case study are selected to compute room acoustic simulations. The meshes are simplified to 2.500 faces and The final acoustically valid three-dimensional mesh is delivered in .ply format with face counts of 10,000, 5,000, and 2,500 faces.

After the geometrical considerations above, three simplification models per case study were selected to compute room acoustic simulations. The meshes were simplified to 2.500 faces. Each mesh includes one sound source position at the frontal stage, shifted 1 meter to the right from the central axis. Several receiver positions were located at distances every 4 meters along the frontal axis to the source, being the first receiver position at 4 meters from the sound source. All room acoustic models were given the same material definitions, and the same source-receiver relative positions.

Room Impulse Responses (RIRs) were computed for each source-receiver combinations and the following room acoustic parameters were derived per octave bands: reverberation time, clarity (C50) and strength (G). Percentual comparisons among the room acoustic parameters across the simplified meshes were analyzed. The room acoustic simulations were computed using the RAVEN software (Schröder and Vorlaender (2011)) from the RWTH Aachen University

Figure 3: C50 values obtained from Raven Simulations variating spacing parameter. Case studies are Left: Santa Agata; Middle: Saló del Tinell; Right: Santa Maria del Mar

5. Conclusion, Limitations, and Outlook

In this study, three case study rooms were scanned and their geometrical models were reduced in complexity to produce room acoustic simulations. The differences in two classical room acoustical parameters (T30 and C50) were quantified for several geometrical reduction parameters. The main conclusions obtained can be listed as follows:

Figure 4: T30 values obtained from Raven Simulations variating spacing parameter. Case studies are Left: Santa Agata; Middle: Saló del Tinell; Right: Santa Maria del Mar

Firstly, we observed that fixing the number of faces to a predetermined value, regardless of the spatial scale, results in disproportionately large faces in areas with lower graphical detail compared to those generated in small or intricate regions. This causes the geometric definition of the model to depend on the level of detail of the space relative to its size and to the degree of simplification applied. For future research, the algorithm could be adapted to incorporate a maximum allowable face size and to relate this constraint to the acoustic frequency range being studied.

Secondly, the biggest differences in reverberation time simulations (T30) across geometrical simplifications is on 2,.1 seconds, especially in the mid-frequency range. Those variations are bigger than the just-noticeable differences, according to literature (Hugo Fastl and Eberhard Zwicker (2007)). This highlights the importance to consider the simplification approaches suggested in the study. The biggest differences in the clarity parameter (C50) shows differences around 1.8 dB, specially in mid-low frequency ranges. Those differences are also bigger than the just-noticeable differences according to literature (Bradley et al. (1999)), highlighting the importance again to care about the simplification algorithms.

Finally, the application of the proposed algorithms and workflow demonstrates that, even when computational resources are relatively high, the actual processing capacity becomes the principal limiting factor when dealing with large, highly detailed environments. Processing times were especially high for Santa Maria del Mar, and we consider this one of the aspects that could be improved in future revisions of the methodology. When data capture is carried out effectively, efficiently, and under controlled conditions as occurred in the Saló del Tinell and in the Chapel of Santa Àgata, the computational cost is significantly reduced. Moreover, avoiding the use of ISPR, achieved when having the normals precomputed, greatly shortens processing time. Consequently, the results indicate that the initial stage of data acquisition is where a greater investment of effort leads to substantial computational savings and a higher degree of control over the final outcomes.

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