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TECHNOLOGY-ENHANCED METHODS FOR INDOOR ACOUSTIC 3D MODELLING

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ABSTRACT

This paper presents a comparison between traditional modelling methods and LIDAR-based tools for the development of indoor acoustic models. To this end, two different models have been developed: one using SketchUp and EASE as a traditional modelling approach, and another created with a mobile application that utilizes LIDAR to model in CadnaR. A comparison was carried out using real measurement data to analyse the trade-off between accuracy and time savings. The findings contribute to the continuous improvement of architectural acoustics, optimizing design strategies. The results may contribute to assessing the potential role of LIDAR-based modelling within the field of acoustic engineering

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1. INTRODUCTION

Given the rapid evolution of autonomous systems and the advancement of task automation technologies in engineering, the development of tools that enhance process efficiency and improve work accuracy has become an essential requirement. This trend highlights the growing demand for high-quality acoustic environments, reinforcing the need for advanced methodologies in architectural acoustics.

Furthermore, architectural acoustics has advanced significantly, driven by improvements in measurement instrumentation, simulation algorithms, and professional expertise in acoustic engineering. Historically, acoustic design relied on empirical knowledge and experimental methods. Today, however, digital modelling tools and high-precision measurement techniques allow engineers to predict and optimize acoustic performance with a level of accuracy previously unattainable [1]. These advancements have led to significant improvements in the acoustic quality of rehearsal rooms, con concert halls, and other performance spaces.

One of the primary challenges in this field is the validation of three-dimensional acoustic models, which play a crucial role in the design and refinement of performance spaces. Traditional modelling approaches, such as those implemented in EASE (Enhanced Acoustic Simulator for Engineers), have been widely used to simulate sound propagation and evaluate room acoustics. However, the integration of LiDAR sensors in applications like CadnaR presents new opportunities for improving model accuracy and efficiency [3].

Nevertheless, it is essential to highlight that model precision is critical in interior acoustic engineering, as simulation software relies on surface area calculations of materials to perform accurate sound propagation modelling. Even small discrepancies in the 3D model can lead to significant deviations in simulated acoustic responses [2]. For this reason, accurate modelling directly impacts the reliability of simulation results, especially in complex rooms with diverse materials and geometries.

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This paper compares and analyzes the accuracy and time efficiency of 3D indoor modelling using LiDAR-based tools (CadnaR) versus traditional methods (SketchUp and EASE). The evaluation is based on a comparison between the simulation results and real-world values obtained through an on-site measurement campaign. The modelling and measurement campaign was conducted in a rehearsal room used by the Real Orquesta Sinfónica de Sevilla, situated in the Teatro de la Maestranza, Sevilla (Spain).

2. ACOUSTIC SPACE AND 3D MODELLING DEVELOPMENT

2.1 Description of the Room Under Study

Designed to host symphony orchestra rehearsals, the room covers an area of 240 square meters with a height of 12 meters, and includes a mid-level balcony intended for choir use. The surfaces consist of a parquet floor, concrete walls partially treated with sound-absorbing materials, and a suspended ceiling. One of the upper walls, above the balcony, features a complex pyramidal design that contributes to the room’s acoustic diffusion.

Figure 1. Photograph of the room under study.

A well-conceived design ensures that the venue is both aesthetically appealing and functionally optimized for sound performance. Architectural elements such as room shape, materials, and reflective surfaces play a crucial role in shaping the acoustic characteristics of a space.

2.2 3D Modelling: Traditional Modelling Method versus LiDAR Modelling Tool

To evaluate the accuracy of acoustic simulations, two distinct 3D modelling techniques were employed:

2.2.1 Traditional Modelling Method. SketchUp & EASE

SketchUp, recognized as an industry-standard software for architectural modelling, enables the creation of detailed and highly accurate spatial representations. The 3D model developed for this study required approximately 32 hours of manual work, ensuring a precise architectural representation of the rehearsal room, ensuring the ability to model complex geometries, such as columns or the upper diffusive area.

2.2.2 LiDAR Modelling Tool

The latest version of Cadna-R integrates LiDAR (Light Detection and Ranging) technology, enabling a rapid three-dimensional scanning of a space using your phone. This approach significantly reduces the time required to develop a room model, completing the scan in just 20 minutes.

LiDAR is a remote sensing technology that uses laser pulses to map the surrounding environment. The sensor emits laser beams that reflect off surfaces, measuring the time it takes for the light to return, a process known as “time-of-flight”. This enables for the rapid generation of highly precise 3D models, which are especially valuable in acoustic simulations, where spatial accuracy directly influences results.

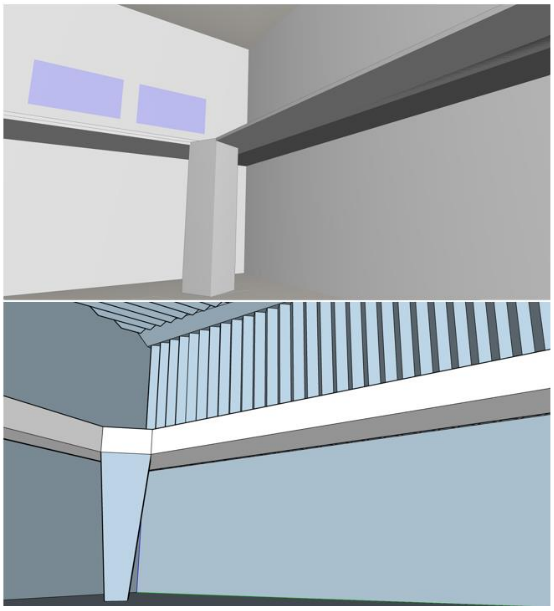

Figure 2. 3D Models: LiDAR Modelling Tool (CadnaR - Up), Traditional Modelling Method (SketchUp & EASE – Down).

2.3 Precision versus Timing

Acoustic simulation software operates based on surface materials and their corresponding absorption coefficients. The accuracy of these models directly impacts the reliability of the simulation results.

A highly detailed model, enables precise surface area calculations, which in turn supports more accurate acoustic performance predictions. On the other hand, this particular detail necessitates a non-negligible amount of time devoted to modelling tasks.

This highlights the importance of balancing precision and efficiency. For applications where rapid acoustic assessment is necessary, LiDAR integration within CadnaR provides a groundbreaking solution. However, for highly specialized acoustic studies, a more detailed manual approach may still be required.

The ability to generate a 3D model quickly with LiDAR demonstrates the trade-off between modelling precision and efficiency. While SketchUp provides superior geometric detail, the automation and speed of LiDAR-assisted modelling in CadnaR present significant advantages for large-scale or time-sensitive acoustic projects.

3. SOFTWARES ANALYSIS

3.1 EASE

EASE, developed by AFMG, is one of the most comprehensive tools for simulating and analyzing room acoustics. It is particularly favored for performance venues, such as concert halls, theaters, and auditoriums, where detailed sound propagation modelling is required. EASE allows for:

- Detailed room modelling with precise material properties.
- Comprehensive acoustic simulations, including reverberation time (RT), clarity indices, and speech intelligibility.
- Sound system design and optimization, making it particularly useful for spaces with electroacoustic reinforcement.

3.2 CadnaR

CadnaR, developed by Datakustik, is widely used in industrial and smaller-scale enclosed spaces where quick acoustic assessments are needed. One of its key advantages is the integration of LiDAR scanning technology, which allows for rapid 3D model creation. CadnaR offers:

- Fast model generation with automated geometry capture.
- Basic acoustic analysis tools, including reverberation time and sound pressure level distribution.
- Less detailed simulations compared to EASE, making it more suitable for quick evaluations and practical design modifications.

Although EASE provides more in-depth simulations, CadnaR's efficiency in model creation significantly reduces processing time, making it an effective tool for preliminary assessments.

4. RESULTS

As stated above, in order to have a realistic comparison, an acoustic measurement campaign was conducted in the rehearsal room following the ISO 3382 standard [4]. This standard defines the measurement of room acoustics parameters, such as Reverberation Time (T30, T20, and T15), Clarity Index (C80), Speech Transmission Index (STI) or Sound pressure level distribution. The measured values have been compared with those calculated by both models in order to assess their accuracy.

The following figure displays the results of the comparison:

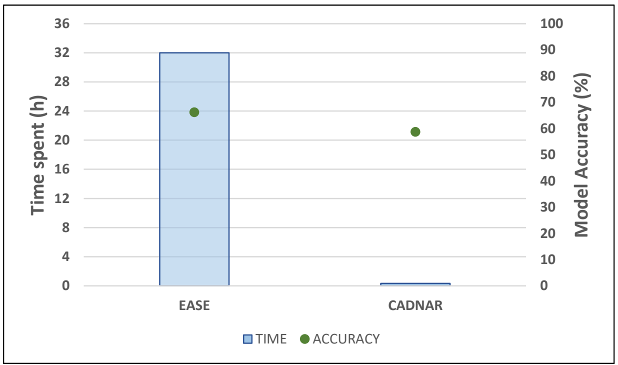

Figure 4. Comparison between Traditional Modelling Methods and LiDAR Modelling Tools.

The comparison between both models shows that, despite the reduction in labor hours, the accuracy of the results decreases by 10% when using the LiDAR-based tool.

5. ANALYSIS AND FINAL CONSIDERATIONS

5.1 Computational Capabilities

EASE and CadnaR offer distinct computational capabilities tailored to different acoustic analysis needs. EASE provides a more detailed and comprehensive simulation environment, allowing for an in-depth analysis of room acoustics, including parameters such as clarity (C80), speech intelligibility (STI), and early decay time (EDT). In contrast, CadnaR is designed for rapid noise assessments and is commonly used in industrial interior acoustics rather than performance spaces. While CadnaR integrates LiDAR scanning technology for fast model generation, its simulation capabilities may not be as detailed or suitable for complex room acoustics studies.

5.2 Execution Time

A key advantage of CadnaR is its significantly reduced execution time. As demonstrated in the modelling phase, CadnaR was able to generate a 3D model within 20 minutes, while the SketchUp model required approximately 32 hours to be completed. However, this speed comes at the cost of reduced modelling accuracy, which can lead to less precise acoustic simulations. EASE, in combination with SketchUp, requires more time investment but ensures that the final simulations are based on a highly detailed and accurate 3D environment.

5.3 Importance of Accurate Modelling

In room acoustic simulations, model accuracy is crucial for obtaining reliable results. The precision of surface area calculations directly influences the material distribution and absorption coefficients used in the simulation. In this regard, SketchUp provides a highly detailed model that accurately represents the geometry and surface areas of the venue. Since acoustic simulation software operates based on the interaction between surfaces and materials, an imprecise model could lead to deviations in the predicted acoustic parameters, reducing the reliability of the study.

5.4 Conclusion

Given the need for high precision in acoustic simulations for performance spaces, EASE, combined with SketchUp modelling (traditional modelling method), proves to be the most suitable choice. While CadnaR (LiDAR Modelling Method) offers a faster approach to modelling and noise assessments, it lacks the computational depth required for accurate acoustic performance analysis. The precision offered by EASE, paired with the highly detailed SketchUp model, ensures that the simulated acoustic conditions closely match real-world performance, making it the preferred choice for projects demanding exhaustive accuracy in acoustic assessments.

Regardless, LiDAR technology holds significant potential and future prospects in the field of indoor acoustics.

6. LIMITATIONS AND FUTURE LINES OF RESEARCH

In any research project that seeks to contribute valuable insights to science, certain limitations are inevitably encountered. In this study, the latest technology available through the CadnaR App has been employed to scan and model an enclosure in real time using LiDAR technology. However, this approach has presented multiple limitations.

6.1 Identified Limitations

Dependence on Proper Illumination: The scanning process was significantly affected by inadequate lighting conditions. Some corners of the enclosure were not properly modelled if they were not well illuminated. This highlights the necessity of controlled lighting conditions to ensure accurate modelling.

Inability to Interpret Multi-Level Structures: The scanning technology struggled with the orchestra pit and balcony present in the rehearsal room. The software did not recognize that there was an additional lower ceiling section, assuming instead a flat ceiling at the balcony level, failing to extend the room to its actual height. This required approximately 30 additional minutes of post-processing to manually adjust and correct the missing structure.

Challenges with Complex Geometries: The system failed to correctly interpret angled walls, sloped ceilings, and structural columns present in the actual venue. While the LiDAR scan efficiently modelled simple, open spaces (such as offices or rectangular rooms), its accuracy was significantly reduced in enclosures with intricate geometries.

6.2 Future Lines of Research

To enhance the efficiency and accuracy of LiDAR-based modelling for acoustic simulations, several advancements should be explored:

Enhanced LiDAR Technology: Improving the scanning technology so that it is less dependent on external lighting conditions. A more advanced sensor capable of capturing geometric data regardless of lighting constraints would significantly improve the accuracy of generated models.

Integration with Drone-Based Scanning: Utilizing drones equipped with LiDAR cameras to navigate multiple levels of the venue would allow comprehensive scanning without missing elements such as mezzanines, balconies, or ceiling irregularities. This approach would also facilitate capturing the total height of the enclosure with higher precision.

Use of Professional-Grade LiDAR Systems: Employing high-end LiDAR systems would substantially increase the precision of spatial modelling, particularly in rooms with complex geometries. However, these systems currently involve a significant financial investment, which may limit their accessibility for smaller-scale projects. Additionally, ensuring compatibility between such devices and mainstream acoustic simulation software—like CadnaR or EASE—poses an additional technical challenge that must be addressed.

Advanced AI-Based Geometry Recognition: Implementing AI-driven algorithms capable of recognizing and interpreting complex architectural elements, such as inclined surfaces, non-rectangular walls, or intricate ceiling structures, would lead to more precise 3D modelling.

Automated Post-Processing and Error Correction: Developing automated software tools that detect and correct common LiDAR modelling errors, such as missing sections or misinterpreted structures, would reduce the need for manual adjustments and post-processing time.

Integration with Hybrid Modelling Methods: Combining LiDAR scanning with photogrammetry could enhance the accuracy of surface texture and material recognition, improving not only the geometric precision but also the acoustic property assignments of different surfaces within the simulation software.

Improved Software Interoperability: Enhancing the compatibility of CadnaR's LiDAR-generated models with other architectural modelling and acoustic simulation software, such as EASE and SketchUp, would create a more seamless workflow, allowing for higher fidelity in simulations.

By addressing these limitations and implementing these improvements, LiDAR-based modelling can become a more robust and reliable tool for acoustic simulation in complex environments, making it an indispensable asset for future architectural and acoustic engineering projects.

7. EQUATIONS

Reverberation Time (RT60):

Reverberation Time (RT60) is the duration required for sound to decay by 60 decibels after the sound source has stopped. It is a critical parameter in room acoustics, indicating how reflective or absorptive a space is. The Sabine formula, applicable for rooms with relatively uniform absorption, is expressed as:

$$\mathrm{RT(s)} = 0{,}161 * \frac{V}{A}; \quad (1)$$

Where:
- V is the volume of the room in cubic meters (m^3).
- A is the total effective absorption area in square meters (m^2), calculated by summing the products of each surface area and its respective absorption coefficient.

This formula assumes a diffuse sound field and is most accurate in spaces where absorption is evenly distributed.

Acoustic Warmth (Bass Ratio, BR)

Acoustic Warmth, quantified as the Bass Ratio (BR), assesses the balance between low and mid-frequency reverberation times. It is calculated as:

$$\mathrm{BR} = \frac{\mathrm{RT(125Hz)} + \mathrm{RT(250Hz)}}{\mathrm{RT(500Hz)} + \mathrm{RT(1kHz)}} \quad (2)$$

Where:
RT_{125}, RT_{250}, RT_{500}, and RT_{1000} are the reverberation times at 125 Hz, 250 Hz, 500 Hz, and 1000 Hz octave bands, respectively.

A BR greater than 1 indicates enhanced bass response, contributing to a sense of warmth in the acoustic environment.

Brightness (Br)

Brightness evaluates the prominence of high frequencies in a room's acoustics and is defined as:

$$\mathrm{Br} = \frac{\mathrm{RT(2kHz)} + \mathrm{RT(4kHz)}}{\mathrm{RT(500Hz)} + \mathrm{RT(1kHz)}} \quad (3)$$

Where:
RT_{4000} and RT_{125} are the reverberation times at 4000 Hz and 125 Hz, respectively.

A higher Br value suggests a brighter sound due to prolonged high-frequency reverberation relative to low frequencies.

Musical Clarity (C80)

Musical Clarity (C80) measures the ratio of early to late arriving sound energy, indicating how clearly musical details are perceived. It is calculated using:

$$C80(dB) = 10\log\left(\frac{\int_{x=0}^{te=80ms} p(t)^2 dt}{\int_{x=0}^{inf} p(t)^2 dt}\right) \quad (4)$$

Where:
- p(t) represents the sound pressure as a function of time.
- The numerator integrates the squared sound pressure over the first 80 milliseconds (early reflections).
- The denominator integrates the squared sound pressure from 80 milliseconds onward (late reflections).

Positive C80 values indicate that early reflections dominate, enhancing clarity, while negative values suggest a prevalence of late reflections, potentially muddling musical detail.

Early Support (ST1)

Early Support (ST1) assesses the support provided to performers by early reflections, particularly in ensemble settings. It is defined as:

$$ST1 = \frac{\text{Energy between 20 and 100 ms}}{\text{Energy up to 20 ms}} \; [dB] \quad (4)$$

Where:
- The numerator integrates the squared sound pressure over the initial 10 milliseconds (very early reflections).
- The denominator integrates the squared sound pressure from 20 to 100 milliseconds (early reflections contributing to ensemble support).

Higher ST1 values suggest stronger early support, beneficial for performers to hear themselves and others clearly.

8. ACKNOWLEDGMENTS

This project required a comprehensive technical setup to ensure precise and standardized acoustic measurements in accordance with UNE-EN ISO 3382 [4]. The accuracy of the measurement stage was fundamental, as the resulting data served as the reference for simulating the real acoustic conditions within the space and validating the virtual models developed during the study.

The instrumentation employed included:

Omnidirectional Sound Source: A dodecahedral loudspeaker conforming to ISO 3382-1 (Annex A.3.1) was used to ensure uniform sound radiation in all directions, providing reliable excitation of the room.

Measurement Microphones: Compact, omnidirectional microphones with a diaphragm diameter not exceeding 14 mm, as indicated in Section 4.2.2.1 of the standard. These were connected to either a signal recorder or directly to an amplifier and analysis unit.

Sound Card: Served as the interface for processing the captured input signals and transmitting them to the analysis software (EASERA).

Signal Amplifier: Used to increase signal amplitude, enabling greater decay times and improving the signal-to-noise ratio, which is essential for accurate room response measurements.

Calibrator: Provided a stable and known reference signal to verify and adjust the accuracy of the microphones and other measurement components, ensuring consistency and reliability in the acoustic data collected.

Sound Level Meter (SPL Meter): Monitored the peak levels generated by the impulsive sound source to avoid saturation in any part of the signal chain, in line with Section 4.2.2.3 of ISO 3382.

Laptop with EASERA Software: Hosted the acoustic analysis software responsible for generating sweep signals, performing real-time measurements, and conducting post-processing. EASERA integrates several analytical modules, allowing a comprehensive and immediate view of the acoustic environment.

During the measurement process, a frequency sweep signal was emitted through the omnidirectional source and captured by the microphone. This signal was then analysed using EASERA to extract all acoustic metrics required by the ISO 3382 standard [4]. This setup ensured a high degree of precision and repeatability in the measurements, providing a solid foundation for the subsequent simulation and analysis phases of the project.

9. REFEENCES

[1] Kuttruff, H. (2016). Room acoustics. Crc Press.

[2] Van der Hoeven, A., & Hitters, E. (2020). The spatial value of live music: Performing,(re) developing and narrating urban spaces. Geoforum, 117, 154-164.

[3] Pizzolitto, E. (2024). Music in business and management studies: a systematic literature review and research agenda. Management Review Quarterly, 74(3), 1439-1472.

[4] ISO, I. 3382: Acoustics-Measurement of room acoustic parameters-Part 2: Reverberation time in ordinary rooms. 2008. Geneva: ISO.