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EXPLORING THE PAST USING DYNAMIC AURALIZATION OF CULTURAL HERITAGE: A CASE STUDY ON THE THEATRE OF TYNDARIS

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ABSTRACT

This work describes the development of an audio-visual virtual reality experience that allows users to explore the evolution of the acoustics of the ancient Theater of Tyndaris (Sicily) across four historical periods: Greek, Hellenistic, Roman, and contemporary. We present an overview of current methodologies for sound-field navigation and then we focus on our solution of choice: the interpolation between multiple Ambisonics Room Impulse Responses (ARIR) computed in Geometrical Acoustics (GA) software. Approximately 500 3rd Order ARIRs have been employed for each sound source in each configuration. A calibrated simulation model of the theater's current state was validated for plausibility, serving as a foundation for the construction of the acoustical models of earlier configurations, based on archaeological evidence. Using these models, we created an immersive VR environment where users can navigate freely within the theater and seamlessly switch between historical periods to experience the variation in the acoustic qualities from any position. The auralization is accompanied by a detailed real-time visual rendering, made in Unity game engine. Through the case study on the theatre of Tyndaris, we showcase the practicality of this technique, its potentials and its limitations.

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1. INTRODUCTION

Dynamic auralization, or "6DoF" (six degrees of freedom), is gaining traction in acoustics thanks to the rise of Extended Reality (XR) technologies. It enables real-time sound simulation where users can move freely in both translational and rotational dimensions while the audio stream is continuously updated. This spatialized audio allows for the exploration of historically significant acoustic environments, such as ancient buildings in their original configurations, which are now inaccessible [1].

Current 6DoF auralization methods include: (a) interpolation between multiple ambisonic Room Impulse Responses (RIRs), (b) sound-field reconstruction, and (c) real-time simulation. The interpolation approach blends RIRs recorded over a spatial grid to support head rotation and translation [2, 3]. Sound-field reconstruction techniques attempt to infer the acoustic field in unmeasured locations, relying on prior knowledge of the sound environment to enhance the fidelity of the estimation [4]. Real-time simulations using the Image-Source Method [5], beam tracing, and mainly ray tracing offer dynamic rendering but require high computational resources and may sacrifice detail [6].

This study focuses on the virtual audio-visual reconstruction of Roman and Greek theatres, a topic of growing interest since the ERATO project [7]. ERATO analyzed the acoustic properties of ancient theatres through comprehensive reconstructions, including period instruments, performance styles, and representations of actors, musicians, and spectators. However, to our knowledge, no study has applied these reconstructions in a virtual reality experience that allows the user to explore the models.

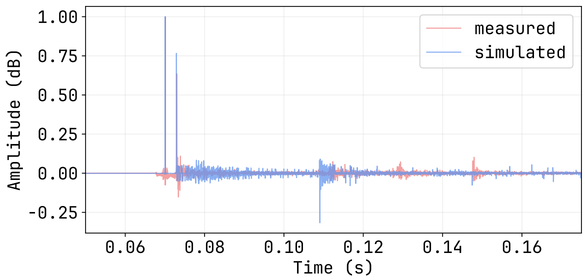
Our approach leverages the interpolation of multiple ambisonic RIRs to achieve dynamic auralization, enabling free movement in three-dimensional space. This methodology lays the groundwork for future applications in immersive heritage experiences.

2. METHODOLOGY

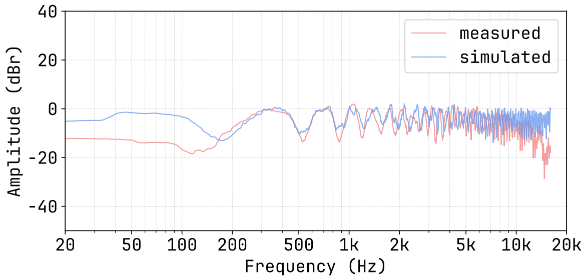
The methodology followed these main steps:

1. The historical development of the site and the evolution of its theatrical configurations were first analyzed;
2. A precise 3D model of the current configuration was constructed and calibrated, serving as a reference for the reconstruction of earlier layouts. This process followed the methodology proposed by Postma and Katz [8], with the acoustic parameters of Strenght (G) and Definition (D50) selected in accordance with Rindel's recommendations for ancient theatres [9];
3. Multiple virtual sources were placed to optimize spatial perception in the simulated environment;
4. Geometrical acoustics simulations of the four historical configurations of the theatre were conducted using Odeon 18 [10] to compute third-order ambisonic RIRs at 535 receiver positions distributed on a 2×2 meter grid over the cavea;
5. The ambisonic RIRs were integrated into a VST plug-in chain, controlled via the Open Sound Control (OSC) protocol;
6. The Unity game engine [11] was employed to send OSC commands to the plug-ins, enabling real-time tracking of user orientation and position;
7. During playback, the three room impulse responses (RIRs) closest to the listener are dynamically selected and interpolated using the RoomZ 1.0.4 plug-in [12] to perform convolution-based auralization.

Figures 1 and Figure 2 present the results of the calibration process at one receiver position, R5 as an example, comparing the measured and simulated IRs in time and frequency domain, and the value of the of the parameters G and D_{50}. Comparable results were obtained across all nine receiver positions distributed in the theater. Preliminary subjective tests, conducted following the protocol in [13], confirmed the perceptual similarity between auralizations based on measured and simulated IRs.

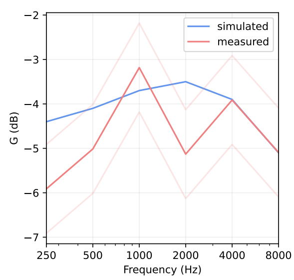


(a) Time domain response

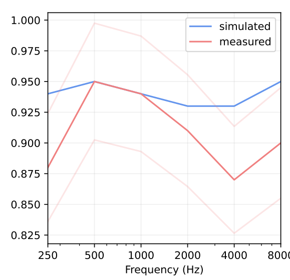


(b) Frequency response

Figure 1: Comparison between measured (red) and simulated (blue) RIRs for receiver R5.



(a) Strength (G)



(b) Clarity (D50)

Figure 2: Comparison between measured (red) and simulated (blue) Strength and Clarity parameters for receiver R5. Dotted lines represent JND limits.

3. HISTORICAL FRAMEWORK

The archaeological site of Tindaris, located on the northern coast of Sicily, reveals various phases of architectural and scenic transformation. In its current configuration, the theater exhibits acoustic degradation due to the loss of its original scenic elements and the erosion of the stone, with wooden benches installed for summer events. The original Greek configuration, dating from the 4th century BC, was later modified during the Hellenistic period by the introduction of the skené, which marked an important evolution in scenic design and significantly enhanced sound reflections. Finally, the Roman configuration adapted the theatrical space for new forms of entertainment by modifying the orchestra area and constructing a podium.

4. IMMERSIVE AUDIO APPLICATION

Our immersive auralizations are based on what we believe to be the only anechoic recordings of historically reconstructed ancient Greek music. These recordings were produced by a research group at Yıldız Teknik Üniversitesi in Istanbul as part of the ERATO project [7]. Excerpts from ancient theatrical plays incorporating both speech and music were performed using reconstructed instruments (Kithara, Aulos, Tympanon, and Scabellum). Captured in an anechoic chamber with four microphones, the recordings were designed for use with the multi-channel method proposed by Otondo and Rindel [14].

The audio processing chain, implemented in Max/MSP [15] and replicable in any DAW supporting third-order ambisonics, is illustrated in Figure 3. In this chain, the anechoic signals are fed into the RoomZ plug-in, which convolves each input with a room impulse response in Ambix format (16 channels).

The 4×16 IR matrix is selected based on the listener's position and orientation, and merged into a single Ambix stream representing the sound field at the virtual microphone's location. The output is then rotated by the SceneRotator plug-in using yaw-pitch-roll data from the Head Mounted Device (HMD), and finally, the BinauralDecoder plug-in converts the rotated Ambix output to binaural audio using standard HRTF filters (with the option to load personalized HRTFs via SOFA files). The Unity project bridges the audio processing chain, the HMD, and the visual models rendered in real time. Based on the OpenXR package, it incorporates a user interface, shown in Figure 4 for navigating between the four historical configurations and a script on the Main Camera that sends OSC streams to comunicate rotational data to SceneRotator, positional data and scene selection to RoomZ.

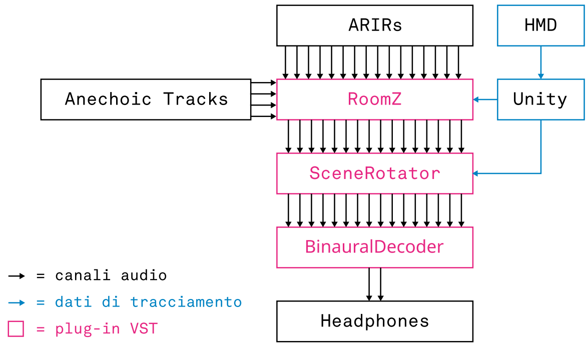


Figure 3: Signal processing chain for dynamic auralization.

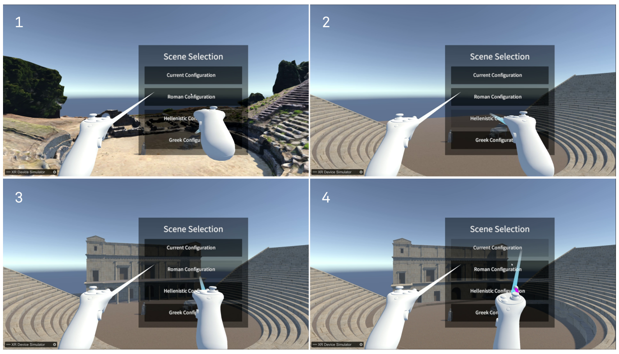


Figure 4: User Interface for navigating between historical configurations.

5. CONCLUSION AND FUTURE PERSPECTIVE

This study has shown the practicality of using a virtual reality experience to explore the acoustics of the ancient Theater of Tyndaris across its Greek, Hellenistic, Roman, and contemporary configurations. By employing a 6DoF auralization approach based on the interpolation of numerous third-order Ambisonics Room Impulse Responses, we recreated the theater's sound field in a way that reflects its historical evolution. His immersive approach can be adapted for use in museums and archaeological sites to enhance public engagement and education. For instance, CAVE systems can offer room-scale shared experiences where visitors walk through historical reconstructions with synchronized 3D audio and visuals. Alternatively, augmented reality (AR) applications for smartphones and AR glasses can bring site-specific acoustic reconstructions directly to users on-site.

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