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Acoustical Heritage: Presentation of the European Project MusicSphere

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Introduction

The preservation of cultural heritage has traditionally been centered on static physical and visual artifacts such as sculptures, paintings, and architecture. However, an equally vital aspect of cultural heritage lies in the acoustic properties of spaces and traditional instruments, as they represent traditional craftsmanship, musical traditions, and performance. The MusicSphere project introduces a multimodal approach for digitizing, analyzing, and simulating classic wind instruments (e.g., hydraulis, organs) by employing three-dimensional scanning technologies, advanced acoustic analysis and reproduction, as well as interactive experiences.

Objectives of the MusicSphere Project

In essence, MusicSphere aims to develop tools that combine advanced technologies for preserving, studying, and providing access to the cultural heritage aspects of traditional musical organs, or in other words: creating digital twins for traditional organs. The project will focus on traditional wind instruments such as pipe organs and their ancient Greek counterparts, such as 'Hydraulis'. Using digital technologies, precise digital replicas of these instruments will be created, capturing intricate physical and mechanical details and aiding in the preservation and restoration efforts. The study will involve an analysis of the unique sound characteristics of the organs and will use acoustic simulations in order to accurately recreate their tonal qualities and the interaction of sound with surrounding architecture and environmental conditions. Virtual and interactive tools will be developed to simulate the handling of these instruments, providing platforms where users can experience them in digital or augmented reality environments.

The technological goals of the project can be summarized as followed:

- holistic digital reproduction of the complete sound production process of cultural heritage musical instruments,
- hierarchical risk mapping of material degradation and environmental conditions,
- preventive maintenance, through the development of musical instruments, digital twins, virtual sensors, and simulation tools,
- dynamic acoustic simulation and binaural rendering for immersive cultural heritage experiences,
- AI-enhanced analysis and synthesis for real-time musical performance reproduction in XR applications.

Beyond preservation of existing organs, the outcome of the project is intended to provide improvements for a variety of users. Historians may benefit from the projection of the results into the past in an effort to approximate the acoustic characteristics of non-functional musical instruments. Digital simulations aid modern organ builders by optimizing airflow, materials, and tuning while maintaining traditional sound. Organists will have the opportunity to virtually play a non-accessible organ or they can experience how a musical piece sounds at various locations in the venue.

In this paper, we want to highlight some challenges related to organ simulation, the characterization of acoustic spaces, and the auralization of organs with the correct room acoustic impression.

Challenge: Simulation of Organ Pipes

To accurately predict sound radiated by an organ pipe, numerical methods like the Finite Element Method (FEM) and Computational Fluid Dynamics (CFD) are invaluable tools. Numerical modeling involves 3D CAD (computer-aided design) to create digital representations of organ pipes. The challenges lie in new pipes typically being handcrafted by organ builders, without available 3D models, and historical pipes often having irregular geometries, which complicates the task of producing their CAD models. It should be noted that even if an appropriate CAD model of an organ pipe is created, it is a challenge to formalize and incorporate the small geo-

metrical changes done by voicers during the voicing step that can alter tone color and attack of organ pipes significantly.

The mechanism of sound generation by organ pipes is very complex and the simulation requires the simultaneous capturing of the nonlinear acoustic field and the hydrodynamic turbulent airflow, both of which strongly interact. Selecting the appropriate numerical scheme, reproducing realistic oscillations of the instrument in full detail is another challenging task. The material properties of organ pipes, both metal alloys and wood, significantly influence the timbre and the attack behavior of the sound. As with pipe geometries, organ builders experiment with different alloys to achieve a desirable sound quality, which makes it difficult to capture precise material properties for digital models. The materials of historic organs may have been subject to alteration caused by aging and varying environmental conditions, such as humidity and temperature. However, if all of the relevant parameters are well-known, simulations can be very valuable. An example of a sound field generated by a 2D simulation of a stopped wooden pipe is shown in Fig. 1.

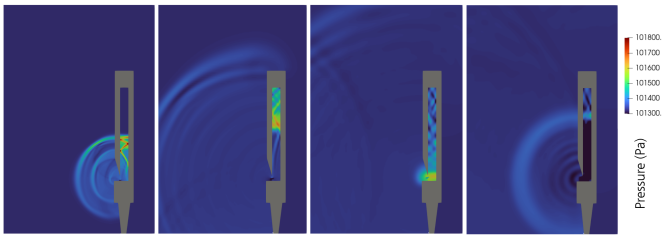


Figure 1: Sequence of a numerical simulation of an operating stopped wooden organ pipe at different time instances. The pressure is indicated by color. Figure after [1]

For the purpose of the later auralization step, the organ needs to be represented in terms of virtual sound sources. Although it seems natural to consider every organ pipe as such a virtual source, it turns out to be a very challenging task. For this, all organ pipes need to be characterized as sound sources with their own tonal and directivity properties. Moreover, depending on organ dimensions and pipe layout, it can be necessary to take into account multiple acoustic scattering of individual pipes by each other.

Typically, an organ consists of many hundreds, sometimes even up to a few ten thousands, of pipes of different types, shapes, and sizes. To avoid time consuming CFD simulations for each and every pipe, it would be beneficial to replicate organ pipes acoustically knowing the sound properties of only some of them. So, another challenge is the development of a parameterization approach allowing for a faster data generation across various pipe geometries without the need for full simulations.

One promising solution to balance feasibility and authenticity of an organ synthesis is a method called differentiable digital signal processing, which offers the possibility to combine neural networks with measured or simulated filters or classic synthesis methods. This approach has been successfully used to resynthesize wind instruments [2] by combining pulsetable synthesis and a neural network to control the parameters of the synthesizer.

Challenge: Characterization of Acoustic Spaces

The perceived sound of a pipe organ results from the complex interaction between the instrument's spatially distributed sound sources and the surrounding room acoustics. To investigate and reproduce these interactions, acoustic measurements are conducted that account for both the spatial variability of the room and the radiation behavior of the organ.

A major challenge arises from the high spatial variance of church acoustics [3, 4]. Measurements are, therefore, carried out at numerous relevant positions using an automated robotic measurement system [5], supplemented by selective manual measurements. The acquired spatial room impulse responses (SRIRs) are used to estimate standard acoustic parameters and directional information, providing detailed insights into the prevailing acoustic conditions. The resulting reference datasets serve to calibrate room simulation models and auralizations, enabling realistic reproduction of organ-specific acoustic characteristics.

The organ represents a large-scale sound source with complex directivity patterns that must be considered. When measuring SRIRs with loudspeakers, sources are positioned directly in front of the organ's primary radiation zones to achieve comparable room excitation.

In addition to room acoustic characterization, recordings of individual pipe tones and combinations from selected stops at varying distances are planned. Microphones are placed at relevant positions inside the organ, close to selected pipes, next to the organ case, at the organist's seat, and within the audience area. These data support pipe modeling, integration of organ signals with measured acoustics, and provide training datasets for machine learning-based sound synthesis. To generate initial datasets and gain practical experience, a measurement series was conducted at St. Jakobus City Church in Ilmenau. The measurement setup is shown schematically in Fig. 2.

Measurements provide valuable reference data for understanding and modeling the acoustic characteristics of churches and organs. However, due to the considerable effort and the large number of required measurement positions, such extensive acquisition is not feasible for future applications. Consequently, the question arises of how the complex acoustic measurement data can be efficiently compressed and transformed into a compact yet meaningful representation. The objective is to enable a complete description of the acoustic environment from a limited set of measurement points by applying suitable methods, thereby establishing the foundation for a realistic and interactively controllable auralization of organ sounds.

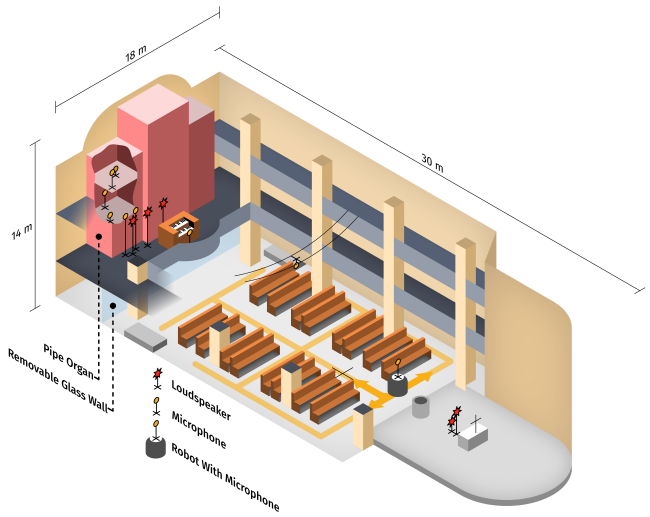


Figure 2: Measurement at the organ and church in Ilmenau as test run and initial dataset for analysis and sound synthesis.

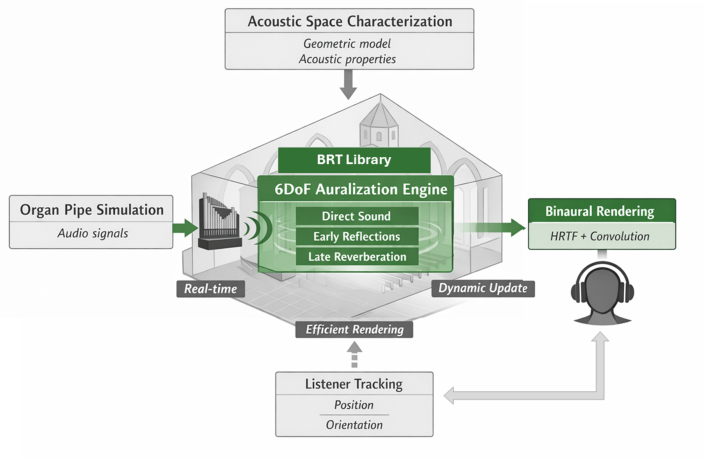


Figure 3: Block diagram of the proposed 6DoF auralization system. Audio signals are processed in real time to simulate direct sound, early reflections, and late reverberation. Listener tracking enables dynamic binaural rendering for an immersive experience.

Challenge: 6DoF Auralization

The third technological challenge addressed in this paper concerns the development of an interactive auralization system capable of rendering the simulated organ sound field within a virtual reconstruction of the church using six degrees of freedom (6DoF). Figure 3 shows the proposed systems. Although the organ constitutes a set of fixed sound sources, the listener is allowed to freely move within the virtual space. This requires a real-time rendering approach capable of dynamically adapting the perceived sound field according to both the listener's position and orientation, reflecting the perceptual variation of movement across the room [6].

The auralization stage integrates the outputs generated in the previous project challenges. On the one hand, the physical and acoustic modeling of the organ pipes provides as an input the sound sources representing the instrument. On the other hand, the acoustic characterization of the church environment provides the spatial and acoustic parameters required to reproduce sound propagation within the space. These components must be combined into a coherent rendering framework capable of producing perceptually plausible spatial audio in real time [7, 8].

A key requirement of the system is the accurate reproduction of spatial hearing cues using binaural rendering techniques based on head-related transfer functions (HRTFs), but supporting full positional tracking of the listener. This implies continuously updating the direct sound, early reflections, and reverberant field as the user moves through the church interior, while maintaining computational efficiency suitable for interactive applications [9, 10].

The resulting framework enables several exploratory use cases. One of them is the integration of the simulation into a navigable virtual reality environment, allowing users to freely visit the church and experience the spatial sound field of the organ from different listening positions. In addition, the acoustic model can be modified to explore alternative scenarios beyond the current state of the building, such as historical configurations of the space, planned architectural modifications, or potential relocations of the organ within the church [11]. Finally, the system allows the exploration of different configurations of the organ divisions and their influence on the perceived sound field across the space [12], offering new possibilities for the study and interpretation of the instrument within its architectural context.

This approach raises several technological challenges, including:

- real-time 6DoF binaural rendering of the organ sound field, capturing the heterogeneity of a large architectural space,
- dynamic update of spatial cues included in direct sound, reflections, and reverberation, according to the listener's position and orientation,
- computationally efficient rendering despite the large-scale environment and long impulse responses required for accurate simulation of the church and supporting interactive exploration and virtual-reality navigation.

Outlook

During the project we aim for the digitization of two to three organs and churches. However, the developed tools should also build the foundation for the preservation of other existing organs and the "revival" of non-functional historic organs. Therefore we want to actively encourage the community to get involved with us. Please feel free to get in touch when you want to know more about the project, explore our tools, or provide feedback! Contact us via wesbite: `https://www.musicsphere-eccch.eu/` or email: `florian.klein@idmt.fraunhofer.de`

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