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From Terrestrial Laser Scanning to Room Acoustics Simulation: Recent Approaches to 3D Modelling for the Investigation of Late Antique and Early Medieval Acoustics.

Gianluca Foschi[1]

[1] Newcastle University, McCord Centre for Landscape, UK, gianluca.foschi@newcastle.ac.uk

ABSTRACT

Recent archaeological investigations of late antique and early medieval acoustics reassess how digital technologies and interdisciplinary approaches shed new light on the history of sound. This paper outlines some of the questions and methodological problems raised by historical acoustics, and discusses digital modelling techniques to tackle them. It shows how information on the acoustics of existing and recreated buildings can be obtained using different datasets and tools.

Keywords: Laser scanning, modelling, intentionality

1. INTRODUCTION

Recently digital technologies allow for acoustics simulations in 3D virtual models of existing, reconstructed, or non-existing spaces. For this purpose, scholars and entrepreneurs have been discussing how to produce models that can be designed in a reasonable time, cope effectively with the limits of available software, and maintain sufficient accuracy to perform reliable simulations [1]. However, modelling has been seldom discussed in relation to the theoretical problems imposed by historical reconstruction. The extent to which different models can be used to address more appropriately some research questions rather than others needs to be carefully considered when reconstructing past acoustics. The present paper explores the interplay between modelling and reconstruction. It focusses on structures built between Late Antiquity and the Middle Ages in the Mediterranean area and in Britain. The acoustic analysis of the case studies is not discussed in detail here as it will be the object of specific forthcoming publications. Instead, this contribution provides a theoretical introduction to the relationship between virtual modelling techniques, research questions, and research outcomes in the study of past acoustics.

2. MODELLING TECHNIQUES APPLIED TO THE STUDY OF HISTORICAL ACOUSTICS

Two typologies of virtual models for digital acoustics simulations are discussed in this paper: 1) Models aimed at reproducing accurately the geometry of a building; 2) Models aimed at reproducing conceptual interpretations of a building.

The first typology is suitable to investigate how the geometry of a space impacts on sound reflection. Their accuracy limits the effect of surfaces deconstruction into polygons – typical of mesh models – on the results of acoustic simulations.

The simplified design of models belonging to the second typology reduces the time of software calculation, and makes them particularly suitable for highly-precise digital simulations of acoustics.

2.1 Models from 3D laser scanning.

Precise structural surveys are necessary to design virtual models that are suitable to investigate the interplay between sound and space. Minimal differences in the orientation of modelled surfaces can dramatically impact on the results of acoustics test [2]. With some exceptions [3], models for acoustics simulation are generally designed after available plans and elevations. However, recent research [4] shows that architectural drawings published in hard-copy can be unreliable for accurate analyses. 3D laser scanning overcomes this problem by providing exceptionally precise surveys. The infrared beam emitted from a laser scanner returns thousands of measured distances per second from the surrounding environment. These measurements can be visualised in software as 3D point clouds. The error range of the correctly processed point cloud of a building rarely exceeds 3 millimetres.

Three buildings have been investigated using digital models derived directly from 3D laser scanning data: the sixth-century basilica of S. Apollinare in Classe near Ravenna (Italy) [4, 5] (Fig. 1, A), the experimental reconstruction – at the local Museum in Jarrow (UK) – of a fifth/sixth century CE timber structure (Building A) excavated at Thirlings in Northumberland (UK) [6, 7], and the rural church of Agios Ioannis Theologos at Adissarou in Naxos (Greece) [8, 9, 10].

Laser scans of each structure were obtained using a FARO laser scanner Focus3D X 330. An optimised triangular mesh was produced from the point cloud of each building using FARO Scene, and exported in the .ply format. Each mesh was opened in MeshLab and re-exported as a .3ds file to be segmented into its main structural elements in Autodesk 3Ds Max Design. The mesh

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was then exported in the .dxf and AutoCAD format to repair its leaks and faulted geometry. All the unspotted leaks were identified in 3Ds Max Design using the "open edges" view and repaired in AutoCAD. Finally, using AutoCAD, the triangles of the mesh were grouped into layers according to the elements and materials that they represent. At this point, the models were imported into ODEON Room Acoustics.

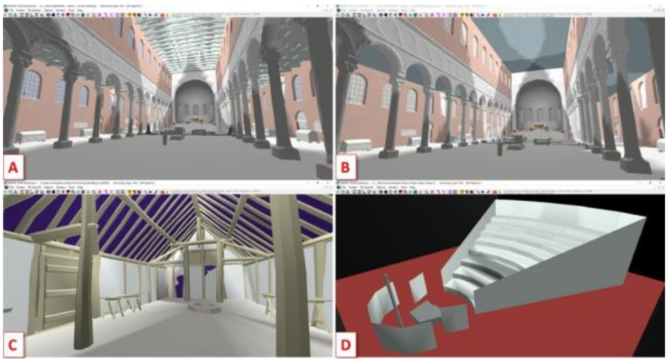

Figure 1 – Selection of 3D digital models of the case studies mentioned in the text, visualised in ODEON Room Acoustics (G. Foschi).

For faster calculations, the meshes were simplified into models with fewer surfaces. To prevent geometrical distortions during the simplification, each layer of a mesh can be imported into MeshLab, its border selected, the selection inverted, and the new selected surface decimated or smoothed to an acceptable extent. Since its borders are untouched, the simplified surface will fit into the rest of the mesh once reimported into AutoCAD. This procedure was applied to the model of Agios Ioannis Theologos at Adissarou. An alternative method is the manual creation of a geometrically simplified "shell-mesh" matching the main features of the digital model. This procedure was applied to the reconstruction of Building A from Thirlings [Fig. 1, C], obtaining a model of 5368 surfaces.

The geometry of the meshes derived from laser scanning can be altered to test different architectural settings and furnishing, or to reconstruct previous phases of the building. This method has been used to explore how acoustics is affected by a coffered ceiling [Fig. 1, B] or a lower presbyterium in S. Apollinare in Classe, by a wooden floor in the reconstruction of Building A from Thirlings, or by other furnishing and architectural solutions in Agios Ioannis Theologos at Adissarou.

2.2 Manually designed models.

The second typology described in this paper is constituted by virtual models reproducing conceptual interpretations of historical sites. Conceptual models convey information beyond the archaeological record and therefore entail historical reconstruction to a larger extent. Gaps in the knowledge of how the features of a building were conceived need to be filled with hypotheses and speculations. Data from excavations, wall stratigraphy, written sources, metrology, and information on design techniques must be critically considered for this purpose. Nevertheless, any outcome of tangible or intangible heritage reconstructions is inevitably influenced by subjective theoretical backgrounds [11]. In order to obtain meaningful results and address unavoidable biases, archaeological theories and historiography [12] must be taken into full account. For this reason, it is best practice to consider a range of alternative hypotheses, and maintain a clear distinction between features designed on the basis of the archaeological record and features that are hypothetically reconstructed [13].

Conceptual models have been adopted for the acoustic analysis of four case studies. The first is the Lateran basilica in Rome (Italy) as it could have been in the 4th century CE [14, 15]. The dimensions of the model were based on the laser scanning survey of the basilica's fourth-century foundations and on a thorough scholarly reconstruction of its possible elevation [14]. The second case study is S. Apollinare in Classe [4, 5]. A total of 3,794 manual and 794 calculated measurements were performed in AutoCAD directly on the point cloud from laser scanning. This enabled the identification of possible units of measurement used during the construction of the basilica, an assessment of its layout quality, and formulation of hypotheses on how the building was conceived. The conceptual model of the building was designed on the basis of these results. The third case study is the wooden 'grandstand' excavated at Yeavering in Northumberland (UK), dated to the 6th/7th century CE [16]. A simplified virtual model of the hypothetical structure (Fig. 1, D) was designed based on excavation drawings published in 1977 [16], which constitutes the most accurate record of the building to date. The last case study is Agios Ioannis Theologos at Adissarou [10]. A thorough archaeological analysis of the church assisted the reconstruction of its possible conceptual design and the study of its chronological phases. On this basis, four virtual models of previous hypothetical buildings were designed to explore how acoustics change according to the main typologies of early churches known on the island of Naxos and in the Mediterranean (e.g. three-aisled vaulted or timber-roofed basilicas, with one or three apses).

3. METHODOLOGICAL RESULTS

3D surveys obtained with terrestrial laser scanning turned out to be an ideal starting point for the analysis of historical acoustics. The use of different typologies of virtual models obtained from them has expanded the range of verifications, research questions and outcomes.

3.1 Published surveys and 3D laser scanning.

The present investigation confirms that published plans and sections do not constitute reliable references for the design of geometrically accurate models. 3D laser scanning has allowed to observe for the first time that the outline of the apse curvature of S. Apollinare in Classe at the plan level is horseshoe-shaped and not semicircular, or that the dome of Agios Ioannis The- ologos at Adissarou is pointed and not hemispherical. These elements have a significant impact on the simu- lation of sound reflection.

3.2 Geometrical precision and acoustic parameters.

Highly precise models are unsuitable for exceptionally accurate acoustics simulations due to the long calculation times that they entail. Nonetheless, even standard simulations performed on them return relevant results. When precise virtual models are used, discrepancies between parameters obtained from acoustic simulations and measured on-site can be attributed with more confidence to incorrect sound properties – e.g. absorption coefficients or scattering coefficients – assigned to the surfaces rather than to geometrical inaccuracy. The sound parameters obtained for S. Apollinare in Classe and the reconstruction of Thirlings' Building A from the models directly derived from laser scanning data were extremely close to on-site measurements [17, 7]. This provided confidence in assigning the same sound absorption coefficients and scattering coefficients to simplified or modified versions of the models, allowing a more firmly grounded exploration of how acoustics change according to the different hypotheses on the configurations and materials of the building.

3.3 Sound reflection in detailed and simplified models.

Models derived from laser scanning and their conceptual simplifications can be significantly different as far as sound reflection is concerned. While their objective sound parameters usually do not show significant differences, the situation changes when sound reflection is visualised, as observed in the case of Agios Ioannis Theologos at Adissarou (Fig. 2). In the model obtained from 3D laser scanning, the dome of the building reflects sound in more directions than in the conceptual reconstruction. This is probably due to irregularities of the dome's inner surface, recorded by the scanner and practically impossible to be manually reproduced. It is therefore important to dispose of both detailed and simplified models for the validation of different typologies.

3.4 Intentionality in past acoustics design.

Precise surveys are a fundamental prerequisite to design reliable conceptual models, which are most appropriate to examine how acoustics would be if the building corresponded to the conceptual project of the designers with no irregularities or later changes. Thanks to the methods described in this paper, elements have been identified suggesting an intentional application of optics to sound reflection between Antiquity and the Middle Ages. This aspect can be exemplified by what has been observed for the acoustic relation between the apse and the nave of the investigated early churches and between the stage and the audience area of the grandstand at Yeavering. In all this cases, the geometry of the semi-circular surfaces generates a sound phenomenon that matches Vitruvius' description of a "circumsonant" place (*De arch*, V, VIII, 2). The voice of a person facing the semi-circular surfaces from a certain distance is reflected towards the focus of the curvature and then laterally dispersed. On the contrary, sound is reflected forward and significantly reinforced when emitted in close proximity of the curved surfaces. This creates a sharp hierarchical differentiation of space by means of acoustics: in the early churches considered here, differences exceeding JNDs in Ts, D_{50}, C_{80} and STI values indicate that an audience standing in the central nave would perceive a voice emitted from the inner limit of the apse – where the *cathedra* and *synthronon* were located – as more clear, loud and intelligible than a voice sounding from the area immediately in front of the apse. Finally, in the Yeavering grandstand, the presence of the semi-circular screening significantly increases the strength of sound inside the structure. These and other recently discussed examples from written sources [18] encourage new research to assess the extent to which acoustic notions were used to model the acoustics of spaces between Late Antiquity and the Middle Ages [15].

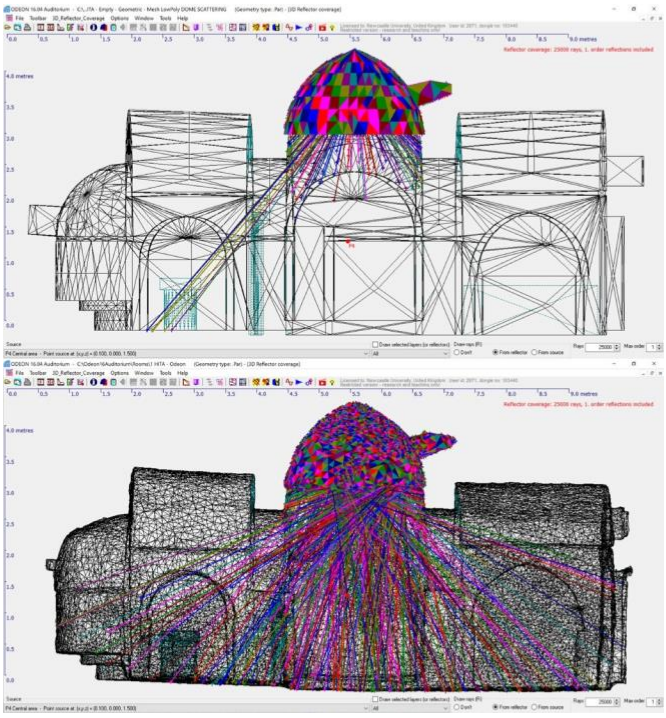

Figure 2 – Agios Ioannis Theologos at Adissarou. 3D Reflector coverage of the dome in ODEON Room Acoustics: conceptual reconstruction (above); model from 3D laser scanning (below) (G. Foschi).

4. CONCLUSIONS

Although highly simplified 3D models are generally used for digital acoustics simulations, the more a model is accurate, the wider is the range of research questions that can be addressed. A reliable geometry in a virtual model used for acoustic simulations favours the identification of sound absorption and scattering coefficients. Furthermore, simplified models producing acceptable results cannot be designed without exceptionally reliable 3D surveys. Only precise models provide correct visualisations of sound reflection, which are fundamental to investigate the application of optics in acoustics between Late Antiquity and the Middle Ages and, more in general, intentionality in historical acoustics.

Although this paper has been concerned with the technical side of modelling it should not be forgotten that sound perception is increasingly recognised as a social construct, subjective rather than objective, and largely dependent on individual backgrounds and historical factors [19, 20, 21, 22]. Its investigation requires a broad theoretical approach combining disciplines such as history, philosophy, sociology, psychology, biology, landscape archaeology, and engineering.

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