3D Reconstruction and Auralisation of the "Painted Dolmen" of Antelas

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ABSTRACT

This paper presents preliminary results on the development of a 3D audiovisual model of the *Anta Pintada* (painted dolmen) of *Antelas*, a Neolithic chamber tomb located in *Oliveira de Frades* and listed as Portuguese national monument. The final aim of the project is to create a highly accurate Virtual Reality (*VR*) model of this unique archaeological site, capable of providing not only visual but also acoustic immersion based on its actual geometry and physical properties.

The project started in May 2006 with *in situ* data acquisition. The 3D geometry of the chamber was captured using a Laser Range Finder. In order to combine the different scans into a complete 3D visual model, reconstruction software based on the Iterative Closest Point (*ICP*) algorithm was developed using the *Visualization Toolkit* (*VTK*). This software computes the boundaries of the room on a 3D uniform grid and populates its interior with "free-space nodes", through an iterative algorithm operating like a torchlight illuminating a dark room. The envelope of the resulting set of "free-space nodes" is used to generate a 3D iso-surface approximating the interior shape of the chamber. Each polygon of this surface is then assigned the acoustic absorption coefficient of the corresponding boundary material.

A 3D audiovisual model operating in real-time was developed for a *VR* Environment comprising head-mounted display (HMD) I-glasses *SVGAPro*, an orientation sensor (tracker) *InterTrax 2* with 3 Degrees Of Freedom (3DOF) and stereo headphones. The auralisation software is based on a geometric model. This constitutes a first approach, since geometric acoustics have well-known limitations in rooms with irregular surfaces. The immediate advantage lies in their inherent computational efficiency, which allows real-time operation. The program computes the early reflections forming the initial part of the chamber's impulse response (*IR*), which carry the most significant cues for source localisation. These early reflections are processed through Head Related Transfer Functions (*HRTF*) updated in real-time according to the orientation of the user's head, so that sound waves appear to come from the correct location in space, in agreement with the visual scene. The late-reverberation tail of the *IR* is generated by an algorithm designed to match the reverberation time of the chamber, calculated from the actual acoustic absorption coefficients of its surfaces. The sound output to the headphones is obtained by convolving the *IR* with anechoic recordings of the virtual audio source.

Keywords: Virtual Reality, Augmented Reality, Auralisation, 3D Acquisition, Laser Range Finder.

1. INTRODUCTION

Virtual Reality is a very active topic of research. A large number of applications of this type of technology can be found in areas as varied as the automotive industry, computer games, industrial training and prototyping, aeronautics, medicine, archaeology, architecture and tourism [1-3]. The European Network of Excellence-INTUITION on this topic joins together more than 58 partners.

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Most of the effort in the design and development of *VR* systems has normally been directed at providing a visually realistic experience to the user. However, whilst vision is undoubtedly our predominant sense, the feeling of immersion in a Virtual Environment can be significantly improved by taking our other senses into account as well. Among them, hearing clearly stands out as the most important for the enhancement of *VR* experiences.

The focus of this work is precisely on the combination of visual and audio immersion; in other words, the reconstruction of a real-world environment through the development of a 3D model which allows the user to see and hear as if she was really there. This requires not only recording the environment's actual visual and acoustic properties and integrating them into the model but also tracking the user's movements and updating the audiovisual scene accordingly in real-time.

The *Anta Pintada* (painted dolmen) of *Antelas* was deemed an excellent case-study for this work. Among the numerous remains from the Neolithic period which can be found in the *Vouga* valley region, this chamber tomb stands out for its extraordinary archaeological value, mainly due to the unique colour drawings found in its interior [4]. Extremely fragile (a considerable part was irremediably lost through exposure to light in early archaeological campaigns), they require strict conservation measures, including severe restrictions to visitor access. This problem – reconciling heritage conservation with the need to provide public access – is by no means exclusive of this particular site. In some cases, the solution has involved building replicas [5, 6]. A less radical, more affordable alternative is offered by the development of *VR* models. These can also be invaluable in the promotion (especially through the Internet) and museological presentation of a site. The heritage conservation authorities responsible for the *Anta Pintada* are very keen on investing in these areas.

Additional motivation for choosing the *Anta Pintada* to test a *VR* model integrating audio is provided by the emergence of *Acoustic Archaeology* [7]: there is growing scientific interest in studying the acoustics of ancient man-made structures. Intriguing acoustic properties have been found in many of them; there is a suggestion that those properties might have been deliberately engineered. The suggestion is particularly strong for Neolithic passage-graves (i.e. composed of a corridor and a burial chamber) such as this one [8].

2. 3D RECONSTRUCTION

3D photo-realistic reconstruction of real-world scenes is not a new topic. Research groups working on it either use systems based on structured light and triangulation schemes or acquire 3D data using Laser Range Finders, which can directly measure distance to points on the environment, generating 'point clouds'. The latter method was chosen, since most structured light systems have ranges in the order of a few metres – too short for this work's needs.

The 3D geometry of the chamber was recorded with a prototype Laser Range Scanner developed at the Centre for Mechanical Technology and Automation (*TEMA*), a laboratory associated with the Department of Mechanical Engineering of the University of Aveiro. A number of scans were carried out in different positions inside the chamber, in order to avoid occlusions as much as possible.

With the help of the Visualization Toolkit (*VTK*), reconstruction software was developed to process the resulting set of 'point clouds' and combine them into a full 3D visual model of the chamber. This reconstruction software, based on the Iterative Closest Point (*ICP*) algorithm, computes the boundaries of the room on a 3D uniform grid and populates its interior with "free-space nodes", like a torchlight illuminating a dark room. The envelope of the resulting set of "free-space nodes" is used to generate a 3D iso-surface providing an approximation of the interior shape of the chamber.

A graphical application was developed to allow further edition, as each region of this iso-surface must be assigned the acoustic absorption coefficient of the corresponding boundary material. Once this operation is completed, an additional module can be accessed to compute the room's reverberation time (RT_{60}), a parameter required in the audio simulation.

2.1 Spatial Data Acquisition

The 3D Laser Range Scanner prototype used in this work is based on a 2D scanner (*SICK LMS 200* laser unit) fixed on a tilt unit to allow rotation. The pan and tilt information are synchronised to produce a spherical representation of points [9]. In May 2006, the prototype was used to acquire 3D information from the "Anta Pintada de Antelas" a Neolithic chamber tomb located in *Oliveira de Frades*, listed as Portuguese national monument (see Figure 1).

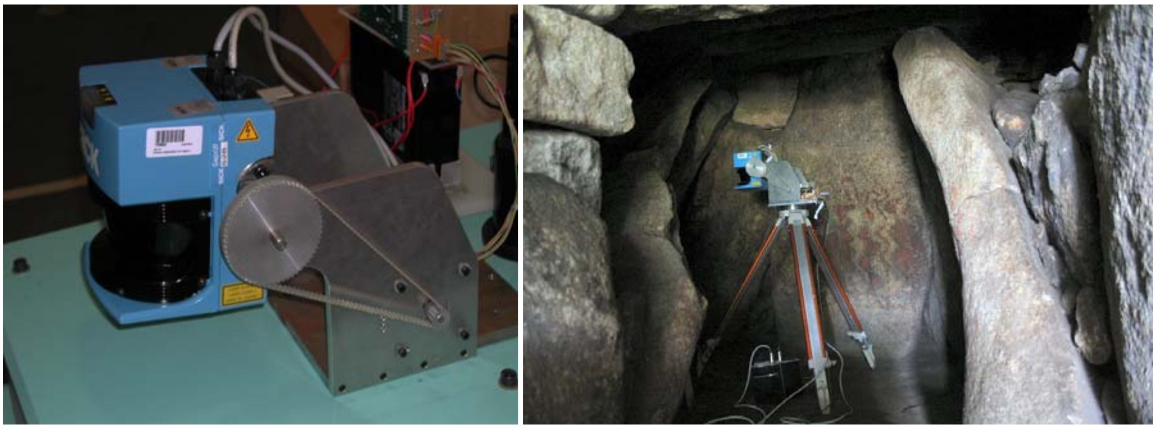

Figure 1: ***(left)*** **3D laser scanner used for spatial data acquisition in the** ***Anta Pintada*** **of Antelas;** ***(right) in-situ*** **data acquisition in May 2006**

2.2 Data processing

For each view, the laser scanner provides a cloud of points. Two examples are shown in Figure 2. These clouds of points must then be processed in order to produce a complete 3D model that can be further edited, analysed and visualized.

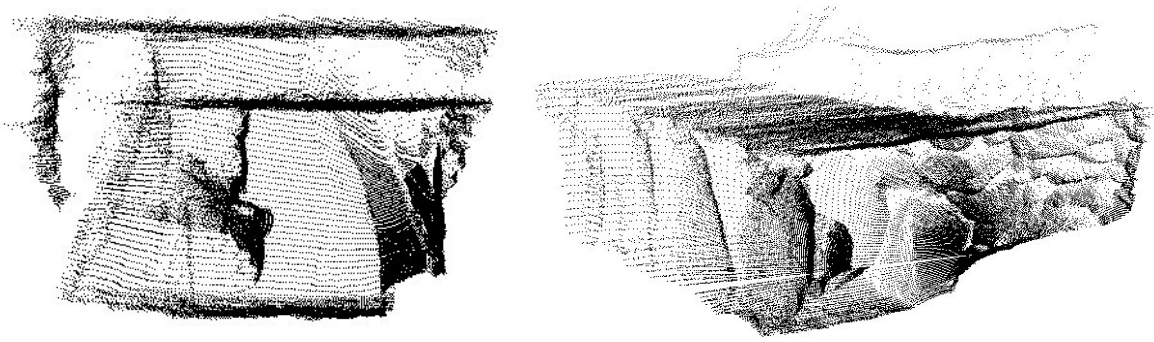

Figure 2: Clouds of points from two views of the ***Anta Pintada***

The first processing step consists in registering all the acquired data on the same coordinate system. The software developed for this purpose, based on *VTK* [10, 11], uses one of the most popular methods of performing this alignment – the *Iterative Closest Point* algorithm (*ICP*) [12]. Two clouds of points can be visualized in the same window; using the interaction facilities provided by *VTK*, the user can manually align them to provide an initial approximation before applying the *ICP* algorithm. The process is then repeated for each of the remaining point clouds. The result obtained after registering the set of 9 range images acquired in the *Anta* is presented in Figure 3.

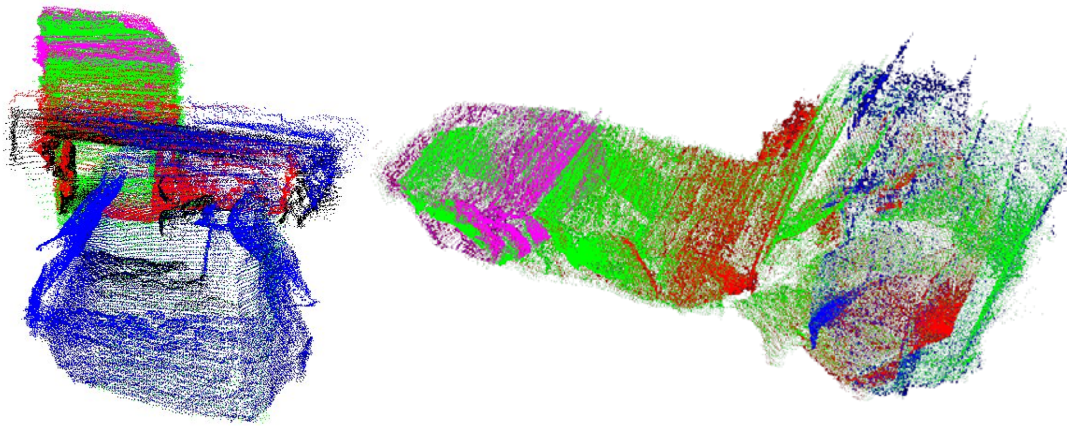

Figure 3: Two views of the complete *Anta* model obtained by aligning a set of 9 point clouds.

2.3 Creation of the final 3D model

Several methods can be used to generate the final 3D triangulated model from the registered cloud of points. The chosen method involves representing the interior of the model as a regular grid and extracting its envelope using contouring methods readily available in *VTK*. The generation of a regular 3D node grid with information on the location of each node (inside or outside the confines of the chamber) is a side benefit of this method, as it can be of help in future developments in the acoustic simulation front.

The algorithm implemented is described in Figure 4. It is applied to all the registered range images and starts by performing a 2D Delaunay triangulation on each. All grid nodes that fall within the viewing volume of the range image are marked. In this way, the algorithm 'illuminates' the nodes with each range image until the whole volume inside the model is marked. A contouring operation on this grid then generates a 3D model of the room, as shown in Figure 5.

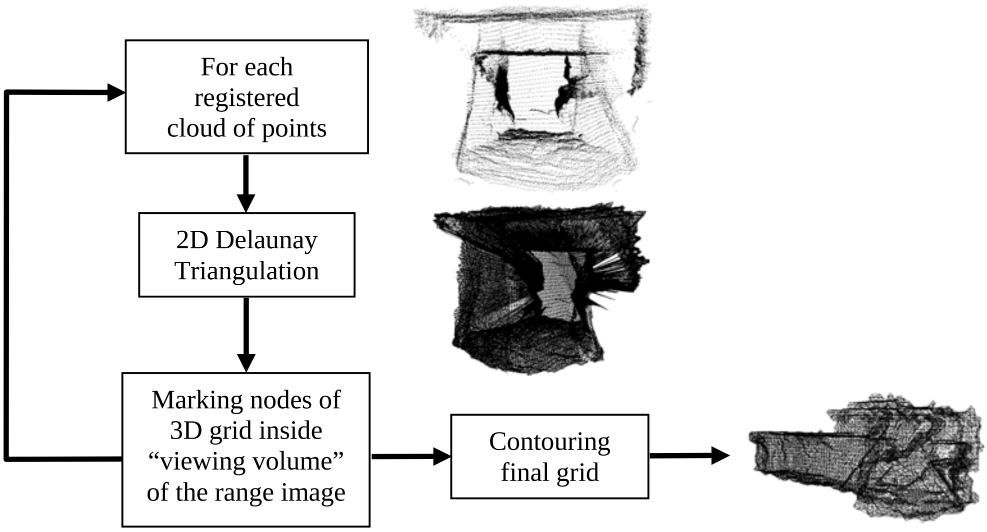

Figure 4: Processing of the registered cloud of points to obtain a 3D model

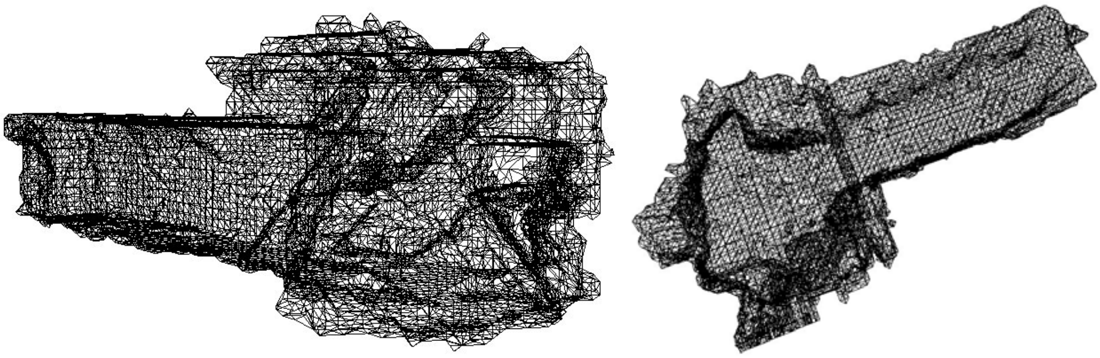

Figure 5: 3D geometric model of the *Anta* after registration and 3D processing

3. AURALISATION

3.1 Room Impulse Response (*RIR*) calculation.

The artificial recreation of an acoustic environment is called auralisation. It consists in reproducing, usually through headphones, the signals that would by heard by a listener in that environment. Given the positions of source and listener, the acoustic behaviour of a room can be described by its impulsional response (*RIR*); in the stereo case, it is called *binaural* since two signals have to be generated (one for each ear). Auralisation is based on the convolution of the binaural *RIR* with anechoic recordings of the sound emitted by the source [13].

There are accurate experimental methods for *RIR* measurement. However, calculating a *RIR* in real time from a 3D model (and achieving convincing auralisation in these conditions) is a complex challenge. The acoustic model must be simplified while keeping the most relevant information from a psycho-acoustic point of view. Typically, geometric models are used. These assume that acoustic waves propagate radially from the source, being reflected by surfaces in the same way as light-beams impinging on a mirror. In their standard formulation, only absorption and reflection phenomena are considered. Assuming there is a direct path from the source, the listener will first hear the **direct sound** from it, then the **early reflections** off the nearest surfaces and finally, after a short time (typically a few milliseconds), a **late-reverberation** tail, characterized by an exponential increase in the density of reflections and a corresponding decrease in their intensity. This is illustrated in Figure 6.

The following sections describe the procedure adopted to obtain a simplified *RIR* from the 3D model of the *Anta*.

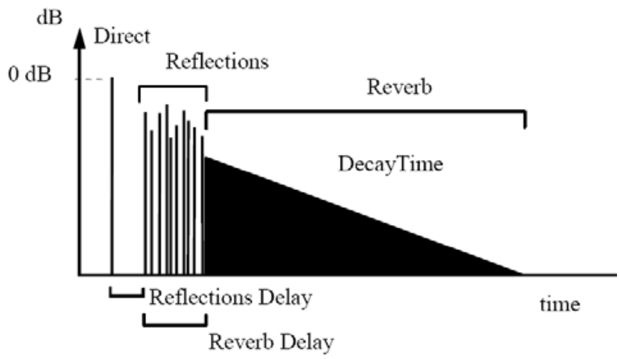

Figure 6: Simplified diagram of an acoustic *RIR*.

3.2 Acoustic characterisation of the 3D model

The 3D model generated by the procedure described in section 2 carries no information on the acoustic properties of the chamber materials. An application was developed to add that information, indispensable for calculating both the early-reflection and late-reverberation parts of the *RIR*. Based on *VTK*, the application allows models to be imported in *VRML* and *OBJ* formats. Among other functionalities, it offers the possibility of selecting single triangles (Figure 7a) or groups of triangles using a *BoxWidget* (Figure 7b) and assigning materials to them, chosen from an *SQL* database containing the acoustic properties of each material. It is also possible to increase or decrease the number of triangles forming a model, to fit the desired model configuration precision.

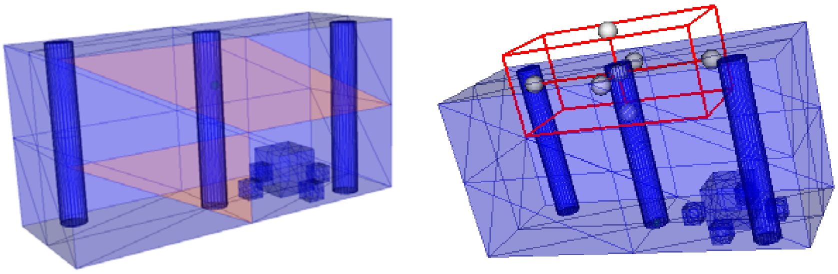

Figure 7: (a) Examples of triangle and (b) *box widget* selection on a synthetic model.

3.3 Early reflections

The direct sound is followed by reflections arriving from different directions with different delays. The simplest way to compute them is the image-source method [14]. In this method, each reflection is replaced by an independent virtual source: adding reflections to the model corresponds simply to adding sources in different virtual locations. This is illustrated in Figure 8, where *A* and *B* represent respectively the locations of source and listener. The first-order reflection depicted can be thought of as being emitted by the virtual source at *A'* (the mirror-image of *A* relative to the reflecting surface). Higher-order reflections (i.e. reflections involving more than one surface) can be considered in similar fashion.

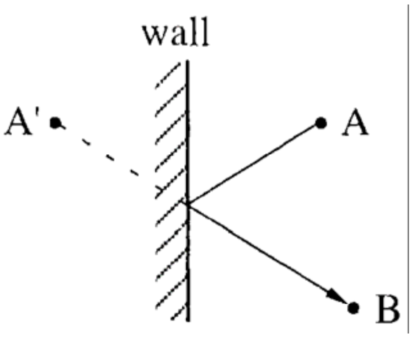

Figure 8: Image-source method.

The most important source localisation cues are provided by the *early reflections* (up to approximately 80 ms delay) forming the initial portion of the *RIR*. In this work, in order to achieve real-time operation, only first-order reflections could be considered, higher-order reflections being simulated by a synthetic late-reverberation tail.

The first step to calculate sound reflections in the 3D model is to work out the position of the virtual sources associated with each triangle. The second step is to check their "visibility", i.e. whether the line between virtual source and listener intersects the corresponding triangle [15]. Figure 9 shows the location of the visible virtual sources (represented by grey spheres) corresponding to first-order reflections in two different models. Source and listener are represented respectively by a sphere and a head.

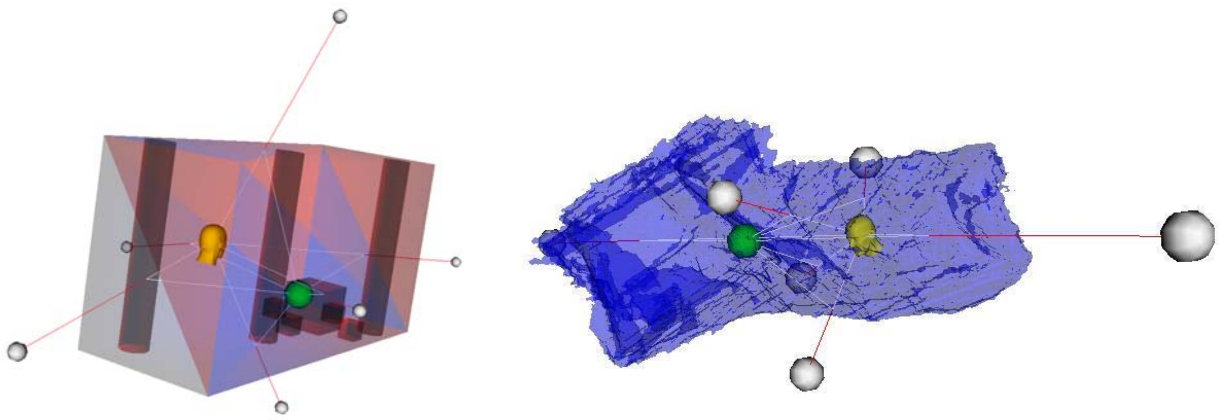

Figure 9: Position of the virtual sources: two examples

The final step is to calculate the attenuation of each sound 'ray', which depends on the distance travelled and absorption coefficients of the reflection surfaces (previously specified, as described in section 3.2).

3.4 Head Related Transfer Functions (*HRTF*)

Before the initial portion of the binaural *RIR* can be constructed from the early reflections computed as described in the previous section, a final aspect must be taken into account: the influence of the listener.

The acoustic stimuli at a listener's eardrums are influenced by the complex interaction between the sound waves and the listener's torso and head (pinna being particularly influential). This interaction is strongly dependent upon the direction of arrival of the sound wave. For each angular position of the sound source relative to the centre of the head (usually specified by two angles: azimuth and elevation), it can be described by a pair of *HRTF* (Head-Related Transfer Functions [16]) – one for each ear. Usually, a discrete set of *HRTF* is defined for regularly distributed values of azimuth and elevation. The *HRTF* capture the main cues on source localisation, provided by the differences in sound intensity and arrival time between ears, known as *Interaural Time Difference* (*ITD*) and *Interaural Intensity Difference* (*IID*).

In Figure 10, $x(t)$ represents the direct sound (an anechoic recording of the sound source) or one of the early reflections (appropriately attenuated and delayed versions of the same anechoic recording). The figure illustrates how these signals are processed through convolution with the *HRTF* filters $h_L(t)$ and $h_R(t)$ (corresponding to the left and right ears), to take into account the interaction with the listener. It should be emphasised that in order to allow real-time auralisation, the *HRTF* used in the algorithm are updated whenever the user moves her head.

The total contribution of the early *RIR* to the output signal, to be reproduced over headphones, is obtained by summing all the partial contributions computed in this way: $x_L(t)$ for the left ear and $x_R(t)$ for the right ear [17].

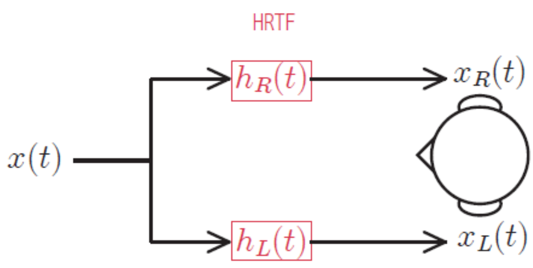

Figure 10: Auralisation diagram

An open source library – *PortAudio* [18] – was used for audio streaming. This library runs on several platforms, ensuring portability.

3.5 Late-Reverberation Tail.

Reverberation, the perceived acoustic ‘spaciousness’ of a room, is one of the most important subjective acoustic parameters. Its most commonly used objective measure is *reverberation time* (RT_{60}) – the time it takes for the sound-field in the room to decay by 60 dB. It depends on the room’s dimensions, shape and materials, being virtually independent from the positions of source and listener [14, 19, 20].

The early portion of the *RIR* is sufficient to provide source localisation cues but far too short to convey any sense of reverberation. It is therefore necessary to add a *late-reverberation tail*. This was implemented using a feedback-delay network (*FDN*). Relatively inexpensive computationally, this algorithm does not hinder real-time operation.

For realism, the reverberation tail must be configured to match the actual RT_{60} of the chamber. This was made possible by the development of an application which calculates the RT_{60} automatically from the 3D spatial data of the model. The Millington-Sette formula is employed:

$$RT_{60} = \frac{0{,}161V}{-\sum_{i=1}^{n} S_i \ln(1-\alpha_i)}$$

RT_{60} : Reverberation time (s)
V: Room volume (m^3)
S_i: Surface area covered by material i (m^2)
α_i: Acoustic absorption coefficient of material i

4. FINAL DEMONSTRATION

The model can be visualised and auralised in a *VR* environment based on a Head Mounted Display (*HMD*), stereo headphones and a 3DOF tracking sensor – see Figure 11. Natural interaction with the environment is possible thanks to the head tracking sensor (*InterTraxII*). This unit constantly updates the *pitch*, *yaw* and *roll* angles which specify the orientation of the user’s head.

Figure 11: Virtual Reality set up: HMD, 3DOF tracking sensor and stereo headphones

An application was developed to test the model by simulating a small virtual concert inside the room under study. During the demonstration, it is possible to separately activate or de-activate each component of the *RIR*: direct sound, early reflections and late reverberation. This allows a better appreciation of their influence in the overall response. It is also possible to individually control the sound sources at different positions in the room. First order reflections can be computed only once, at the beginning of the demo, since the user’s position in the room is fixed: only head orientation is detected. During the demonstration, both the visual scene (showing the positions of both real and virtual sound sources) and the audio scene are adjusted in real time to the head orientation returned by the tracker. Figure 12 presents snapshots of two demonstrations using this application.

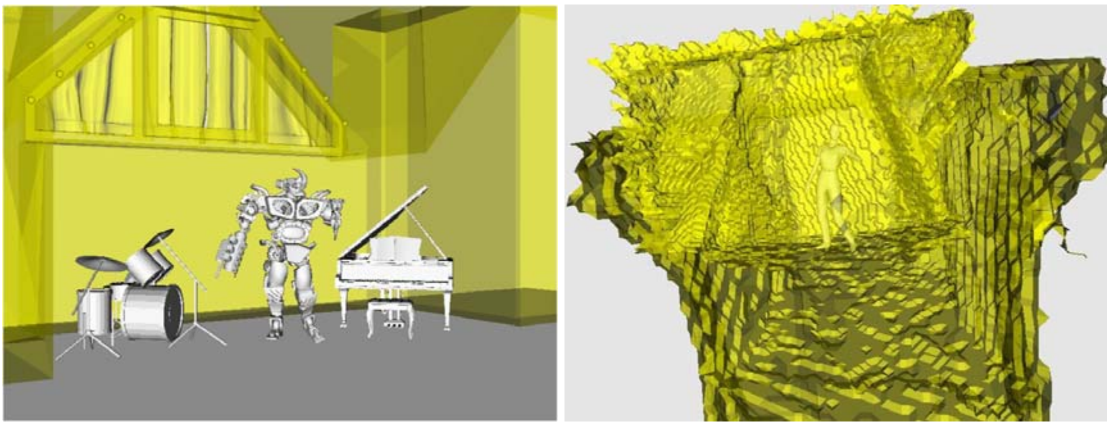

Figure 12: Demonstrations using (*left*) a synthetic model and (*right*) the *Anta* model

5. FUTURE WORK

So far, the main emphasis was on obtaining a geometric approximation of the real room suitable for testing the auralisation algorithms. The main development envisaged in the short-term is to map texture onto the model. On the acoustic front, it will be relatively straightforward to consider frequency-dependent absorption coefficients, with impact on the calculation of both early reflections and reverberation time. Frequency-dependent air absorption should also be taken into account in the late-reverberation tail generation algorithm. Further work is required to optimise the transition between the early part of the *RIR* and the late-reverberation tail. The possibility of extending the early *RIR* by including higher-reflections should be studied. Given the characteristics of the Anta (and similar Neolithic chambers) – small size and very irregular surfaces – the exploration of more complex and potentially realistic acoustic modelling techniques (e.g. physical modelling) is envisaged in the medium term.
The next major stage of the project will be to carry out validation and usability tests. These may suggest preliminary applications in the context of heritage museological presentation and promotion. Tracking user movements in the room is likely to be the following step; this will require a position sensor in addition to the head orientation sensor currently in use.

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REFERENCES

1. Brooks, F.P., *What's real about virtual reality?* IEEE Computer Graphics and Applications, 1999. **19**(6): p. 16-27.
2. van Dam, A., D.H. Laidlaw, and R.S. Simpson, *Experiments in Immersive Virtual Reality for Scientific Visualization.* Computer & Graphics, 2002. **26**: p. 535-555.
3. Zajtchuk, R. and R.M. Satava, *Medical applications of virtual reality.* Communications of the Acm, 1997. **40**(9): p. 63-64.
4. *IRHU Inventory - URL-http://www.monumentos.pt/Monumentos/forms/002_B1.aspx*.
5. *La Grotte de Lascaux. URL-http://www.culture.gouv.fr/culture/arcnat/lascaux/fr/*.
6. *Brú na Bóinne Visitor Centre - Newgrange and Knowth. URL-http://www.heritageireland.ie/en/MidlandsEastCoast/BrunaBoinneVisitorCentreNewgrangeandKnowth/*
7. Devereux, P., *Stone Age Soundtracks: The Acoustic Archaeology of Ancient Sites.* London, 2001: Vega.
8. Jahn, R.G., P. Devereux, and M. Ibison, *Acoustical resonances of assorted ancient structures.* Journal of the Acoustical Society of America, 1996. **99**(2): p. 649-658.

9. Dias, P., M. Matos, and V. Santos, *3D reconstruction of real world scenes using a low-cost 3D range scanner.* Computer-Aided Civil and Infrastructure Engineering, 2006. **21**(7): p. 486-497.
10. Schroeder, W., K. Martin, and B. Lorensen, *The Visualization Toolkit An Object-Oriented Approach To 3D Graphics, 4th Edition*: Kitware, Inc. publishers.
11. Schroeder, W.J., et al., *The Visualization Toolkit User's Guide*. 2001: Kitware, Inc publishers.
12. Besl, P.J. and N.D. Mckay, *A Method for Registration of 3-D Shapes.* Ieee Transactions on Pattern Analysis and Machine Intelligence, 1992. **14**(2): p. 239-256.
13. Farina, A. *Convolution of anechoic music with binaural impulse responses*. in *Proc. of PARMA-CM Users Meeting*. 1993. Parma - Italy.
14. Gardner, W.G., *Chapter 3. Reverberation Algorithms*, in *Applications of digital signal processing to audio and acoustics / edited by Mark Kahrs, Karlheinz Brandenburg*, M. Kahrs and K. Brandenburg, Editors. 1998: Boston.
15. Savioja, L., et al., *Creating interactive virtual acoustic environments.* J. Audio Eng. Soc, 1999. **47**(9): p. 675-705.
16. Gardner, B. and K. Martin, *HRTF Measurements of a KEMAR Dummy-Head Microphone, MIT Media Laboratory*. 1994.
17. Kendall, G.S., *A 3-D sound primer: Directional hearing and stereo reproduction.* Computer Music Journal, 1995. **19**(4): p. 23-46.
18. PortAudio, *an Open-Source Cross-Platform Audio API. URL-http://www.portaudio.com*.
19. Dahl, L. and J.-M. Jot. *A reverberator based on absorbent all-pass filters*. in *COST-G6 Conference on Digital Audio Effects DAFx'00*. 2000. Verona, Italy.
20. Begault, D., *3-D Sound for virtual reality and multimedia*. 1994: Academic Press.