ARCHAEOLOGY AND VIRTUAL ACOUSTICS. A PAN FLUTE FROM ANCIENT EGYPT

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ABSTRACT

This paper presents the early developments of a recently started research project, aimed at studying from a multidisciplinary perspective an exceptionally well preserved ancient pan flute. A brief discussion of the history and iconography of pan flutes is provided, with a focus on Classical Greece. Then a set of non-invasive analyses are presented, which are based on 3D scanning and materials chemistry, and are the starting point to inspect the geometry, construction, age and geographical origin of the instrument. Based on the available measurements, a preliminary analysis of the instrument tuning is provided, which is also informed with elements of theory of ancient Greek music. Finally, the paper presents current work aimed at realizing an interactive museum installation that recreates a virtual flute and allows intuitive access to all these research facets.

1. INTRODUCTION

Sound and music computing (SMC) is a research field with an intrinsic vocation to multidisciplinarity, well exemplified in the project presented here, which combines a team of researchers in such fields as archaeology, 3D scanning and modeling, materials chemistry – as well as SMC – around a unique artistic artifact: an exceptionally well preserved ancient pan flute, probably of greek origins, recovered in Egypt in the 1930's and now exhibited in the Museum of Archaeological Sciences and Art (MSA), University of Padova. Presenting this musical instrument to the general public is a complex task, because of its multi-faceted nature. It is necessary to effectively communicate aspects related to history, iconography, acoustics, musicology, etc., as well as the research carried out during the project.

Starting from this case study, the project aims at defining a novel approach and methodology to "active preservation" of archeological artifacts, and specifically musical instruments. Preservation of documents is usually categorized into passive preservation, meant to protect the original documents from external agents without alterations, and active preservation, which involves data transfer from the analogue to the digital domain [1]. The traditional "preserve the original" paradigm has progressively shifted to the "distribution is preservation" idea of digitizing the content and making it available in digital libraries [2].

We aim at transposing these categories to the field of physical artifacts and musical instruments: passive preservation is meant to preserve the original instruments from external agents without altering the components, while active preservation involves a redesign of the instruments with new components or a virtual simulation, thus allowing access to them on a wide scale. These concepts may be summarized in a single "mission statement": we want to bring back to light archeological remains, but also to bring them back to life, with the aid of technology.

The final goal is to develop an installation that re-creates the instrument, allowing museum visitors to interact with it and its history. Achieving this goal requires truly multidisciplinary methodologies as it entails (i) studying the history and iconography of pan flutes, with a focus on Classical Greece; (ii) analyzing the geometry, construction, age and geographical origin of this artifact through non-invasive techniques such as 3D scanning and materials chemistry; (iii) studying its acoustics, timbre, and tuning, also by combining physics with elements of ancient Greek music theory; (iv) designing interactive installations that recreate a virtual flute allowing intuitive access to all these facets.

The remaining sections touch upon all of these points, with the main goal of illustrating the research methodologies and their potential, while only preliminary results obtained in the early months of the project will be discussed.

2. PAN FLUTES

2.1 A unique artifact

Amongst the archaeological items recovered during the recent reassessment of the MSA in Padova, there is an exceptional musical instrument, an ancient pan flute, probably of greek origins, consisting of 14 reeds of different lengths held together by ropes and a natural binder, and originally coated with a resin layer (now partially missing).

The artifact is one of several objects arrived in Padova thanks to archaeological researches of Carlo Anti, who directed the Italian Archaeological Mission in Egypt since

Figure 1. the pan flute in the box for photographic plates, before restoration (photo by Team EgittoVeneto).

Figure 2. The restored flute (photo by Nicola Restauri).

1928, and led excavations in the ancient village of Tebtynis in the Fayum oasis, from 1930 to 1936, assisted by the italian-english archaeologist Gilbert Bagnani. The flute was stored in a box, originally made for photographic plates (see Fig. 1), which probably belonged to Bagnani, as documented by a short note in the interior. The box cover instead reports a sentence in French in the tiny handwriting of Bagnani's wife, which sets the original finding in Saqqara, from the area of the Mastaba n. XV, thus near Pepi II's tomb. A further information is found in Anti's archive and in a letter written by Evaristo Breccia (Director of the Archaeological Museum of Alexandria), in which he asked about this instrument which he saw in Tebtynis.

This origin is supported by the presence in Padova of other antiquities from Bagnani's campaigns, stored in smal l boxes like the one of the flute, and unlike other archaeological materials. Except for a few exceptions, the findings recovered at the MSA are from 1935, therefore this is probably the year of the discovery of this pan flute too.

The flute was first exhibited at the exhibit “Egypt in Veneto” (April-June 2013), in the section hosted at the MSA and devoted to “The excavations of Carlo Anti in Egypt”. On this occasion, it underwent a major restoration programme for consolidation and preservation [3], as shown in Fig 2. This allowed not only to save the artifact but also to obtain the first analytical data useful to set the continuation of the research. In particular, infrared (IR) investigations found no evidence of earlier decorations, ultraviolet (UV) X and-ray investigations assessed the status of conservation, and chemical analysis tested the related techniques of construction. The flute is currently exhibited at MSA, in a dedicated show-case with air-tight and continuous monitoring of environmental conditions.

2.2 Related literature and iconography

Although its excellent preservation makes this artifact a unique archaeological item, literary and iconographic references to pan flutes are abundant in Greek-Roman world.

The syrinx (*syrìzo*: whistling, playing the bagpipes) appears in the most ancient Greek sources: in Homer's Iliad it is mentioned as an instrument related to the pastoral field (XVIII, 526) and festivals (X, 13), while in the Homeric Hymns it is connected to divine figures such as Hermes (IV) and Pan (XIX). In the Roman world both these aspects are recalled by several authors. In the Metamorphoses (I, 689-712) Ovid tells the story of the god Pan, when he saw the nymph Syrinx, devoted to Diana and so similar to the goddess that the two could not be distinguished. The nymph, at the sight of the monstrous body of the god, fled through inaccessible places, but had to stop on the swampy banks of the Ladon river, her father, where she prayed her sisters to disguise her in order not to be taken. When Pan reached her, all he found was a bundle of reeds. He sighed and the wind on the reeds produced a faint sound, a lament; the god, hit by its sweetness, said: “This conversation between you and me will last forever” and so “welded with wax some unequal reeds and the name of the girl lived forever.” Thus, poetically, the invention of a simple and universal instrument is told.

Ovid in the Tristia (V, 10, 25) mentions pitch as another type of binder for the pipes. In his Onomastikon (IV, 69) Julius Pollux, who lived in Egypt during the 2nd century A.D., describes the syrinx as a structure “of many pipes” or “many sounds” formed by a series of reeds put together from the largest to the smallest and joined with flax and wax, leveled at one end and with a wing-like form. It is usually played by bringing it to the mouth and its musical potential is amazing: it is possible to play the flute, accompany with the flute, and stun with the flute. Pollux (IV, 77) also recalls that a “flute of many notes, discovery of Osiris” was in use among the ancient Egyptians.

In the Archaic period iconographic sources become even richer, both in Greek context, as in the François Vase depicted in Fig. 3(a), and in the Italic one, as in the contemporary (6th century B.C.) Certosa Situla in Bologna depicted in Fig. 3(b). Starting from the Hellenistic-Roman era, the representation of the pan flute spreads enormously, particularly in the Pompeian area: see Fig. 3(c). On the basis of the sources, it can be stated that until the classical period the instrument was quadrangular and made by pipes of equal external length (as in the François vase), while during the Hellenistic era the instrument was wing-shaped with unequal canes. The number of the elements is generally in the range $3-9$ during the Archaic period, $4-10$ in the classical period, and $4-18$ in the Hellenistic period: some Greek sources cite flutes with nine “voices”, while the number seven is preferred in Latin authors [4, 5].

3. NON-INVASIVE ANALYSIS

3.1 3D laser scanning

A 3D model of the flute was acquired using non invasive and non-contact techniques. In order to inspect the sur-

(a) (b) (c)

Figure 3. Iconographic sources: (a) the François Vase; (b) the Certosa Situla in Bologna; (c) a fresco from the Villa of the Mysteries in Pompeii.

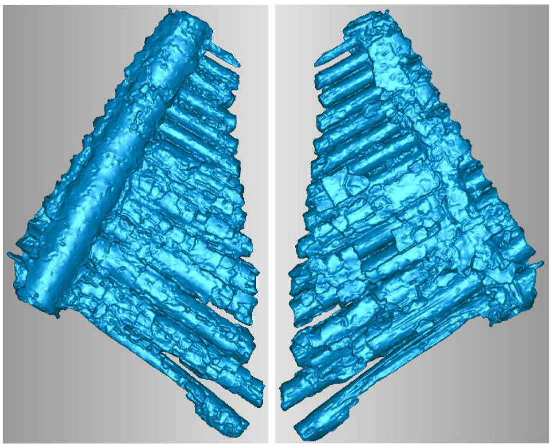


Figure 4. Very high resolution model of the flute.

faces (front and recto) and the border too, a ScanArm V3 from Faro was used. This is a seven-axis measurement system with a fully integrated laser scanner with a scan rate up to 19200 points/s and an accuracy of ± 35 μm. The field depth is 85 mm, and up to 640 points/row can be acquired. We followed a rather standard processing pipeline, which started with raw data acquisition (more than 4.5 million points for each side). At decimation of triangle meshes, more than 470000 triangles were obtained for each side.

In the alignment phase, various scans from different views were mosaicked to obtain the fused model that can be studied in a virtual space performing also metric measurements. In the post-processing phase, additional tools (specifically, Mesh Doctor in the Geomagic software environment) were used to fill holes and to automatically detect and correct errors in the polygonal mesh. As a result a very high resolution model composed by 920152 triangles was obtained, which is shown in Fig. 4.

Metric measurements were performed on this model in order to extract the main relevant parameters for subsequent analysis of the flute acoustics and tuning. Specifically, for each pipe the external length l and the diameter d were estimated. Additionally, in order to obtain a more reliable estimate for the diameter, for each pipe it was estimated along the x-axis (d_x) and the y-axis (d_y), both at the top and at the bottom ends of each pipe. Figure 5 shows

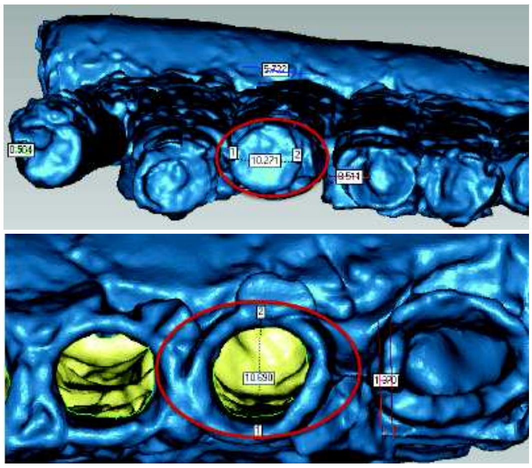


Figure 5. Examples of measurements of pipe diameters: d_x at the bottom end of the third pipe (upper panel), d_y at the top end of the second pipe (lower pipe).

two example measures of d_x and d_y.

Table 1 reports the estimated external lengths and diameters for all the 14 pipes.

3.2 Analysis of the pipe coating

Non-destructive mineralogical investigations were carried out on the two surfaces of a fragment of the coating, by X-ray Diffraction (XRD) coupled with Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS). The external surface (see Fig. 6) shows contaminations by soil sediments (quartz, calcite, anhydrite, kaolinite, albite) and the presence of evaporitic minerals like gypsum and halite (commonly known as rock salt), which are of particular interest since they correlate strongly to the depositional context: the presence of halite and gypsum suggests a depositional context rich in water and with a high evaporation rate like the Fayum oasis. The internal surface also shows quartz, calcite, albite, and wedellite, a common authigenic calcium oxalate related to the reaction between soil and organic matter. Microchemical investigations through SEM-EDS highlighted that halite is distributed all around the sample as shown by the white plaques (see Fig. 7). The sample has high concentrations

Pipe	l	d_x	d_y	d_x	d_y
		(bottom)		(top)	
1	145.56	11.983	11.404	17.981	11.292
2	144.563	12.943	10.089	10.635	10.69
3	127.976	10.271	10.481	10.798	10.366
4	117.315	10.742	9.559	10.671	10.748
5	110.685	11.787	9.243	10.037	9.706
6	96.512	7.394	8.417	9.097	8.98
7	86.397	9.535	6.981	7.787	9.672
8	81.327	8.704	6.546	8.446	8.663
9	71.795	7.251	7.129	6.86	8.109
10	64.341	6.566	6.093	7.63	7.629
11	58.862	6.889	6.222	7.561	6.879
12	51.42	5.616	5.795	5.989	6.562
13	49.554	5.838	5.307	5.423	6.042
14	43.655			4.659	4.731

Table 1. Main flute parameters extracted from the model. All lengths are expressed in mm.

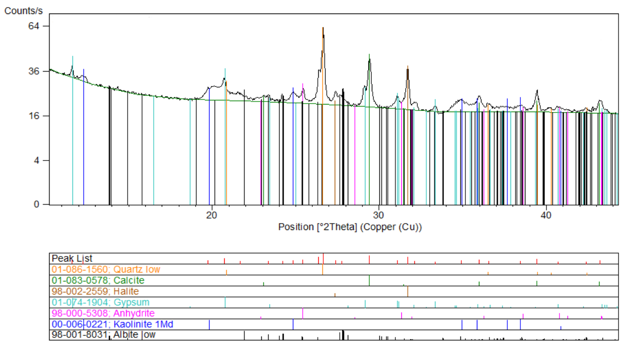


Figure 6. Diffraction pattern of the investigated sample, external surface

of carbon and oxygen, and this provides evidence that the coating is an organic compound.

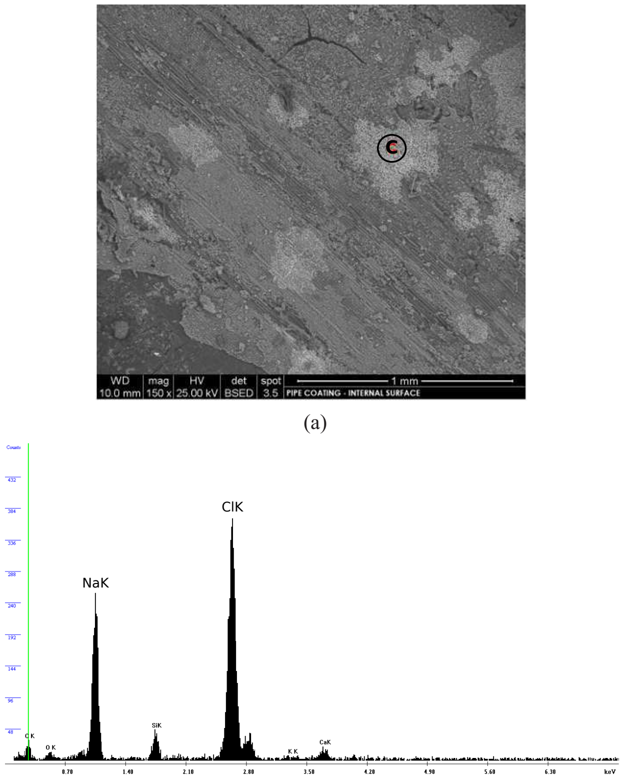
The sample is mainly constituted by an homogenous, lustrous, brittle, brown matrix of organic nature. It is likely to be resin, as confirmed by the elemental composition, but it may also be pitch, tar or bitumen. The investigation on the chemical composition of the coating is still in progress using IR and Raman analysis, and possibly Gas Chromatography-Mass Spectrometry (GC-MS) for the identification of the organic compound. The response will be of high interest to understand the production techniques used for this type of ancient musical instruments, also in comparison to what is known from classical literary sources.

The sample also exhibits a thin vegetal layer detached from the external surface of the pipes, therefore botanic investigations may determine the botanic species of the pipes. Once the nature of the coating matrix will be identified, it may be possible to carry out absolute ^{14}C carbon dating, if its vegetal derivation will be confirmed.

4. THE VIRTUAL FLUTE

4.1 Acoustics and tuning

The measurements discussed in the previous section are the starting point for an analysis of the tuning of the flute.



(a)

(b)

Figure 7. Microstructural and chemical analysis of the investigated sample: (a) SEM image showing white plaques of NaCl; (b) EDS spectrum of the white plaques in the area marked with a "C" showing high Na and Cl peaks.

While most flutes (the transverse flute, the recorder, etc.) are made of jet-excited unstopped pipes (i.e. open at both ends), the pan flute is peculiar in that it is a stopped-pipe wind instrument, thus requiring ad-hoc examination of its aerodynamics [6]. For the sake of our analysis, the first important consequence is that the fundamental frequency f is half that of an unstopped pipe of the same length:

$$f = \frac{4c}{l_{\text{int}} + \Delta l} \qquad \text{Hz}, \tag{1}$$

where c is the sound velocity, l_{int} is the internal pipe length, and $\Delta l \sim 0.305 d_{\text{int}}$ is the length correction at the open end, proportional to the internal pipe diameter d_{int} [7, Ch. 8].

Unfortunately currently available metric measurements do not allow to infer reliable estimates of the internal lengths l_{int}. In fact, it is known that these were reduced by carefully increasing the thickness of the closures through addition of wax or propolis or other organic materials [8], thus achieving fine tuning. Computed axial tomography (CAT scan) may show the internal thickness of the occluding organic material, but this analysis has not been performed yet.

Given the limitations of currently available data, our preliminary estimation of tone frequencies uses Eq. (1) where l_{int} is estimated from Table 1 and a 5 mm-thick closure is assumed at the bottom of the pipes. Internal pipe diameters d_{int} are also estimated from Table 1, by averaging the four measures $d_{x,y}$ at the bottom/top ends, and then subtracting the wall thickness (estimated on average in 1.5 mm).

Pipe	2	3	4	5	6
f Hz	588.25	666.10	726.30	770.72	895.84
Pipe	7	8	9	10	11
f Hz	1001.14	1068.32	1222.43	1373.71	1507.45

Table 2. Tone frequencies estimated from current metric measurements.

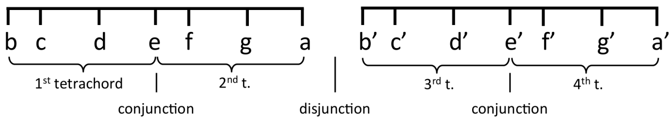


Figure 8. The Greater Complete System.

Table 2 reports the estimated tone frequencies for pipes from 2 to 11 only, since the first pipe is broken and since the approximation in current metric measurements introduces large errors in shorter pipes (from 12 to 14). The estimated frequency for pipe 2 corresponds approximately to a D5 in modern terms. The first obvious observation is that the tuning is consistent with a heptatonic scale, as the pipe pairs $2-9$, $3-10$, $4-11$ are all in a slightly sharp octave ratio (more precisely, the relation $f(\text{pipe}+7)/f(\text{pipe}) \sim 2.07$ holds for pipe$= 2:4$). This slight and uniform detuning may be due to our use of constant 5 mm-thick closures, which overestimate the frequencies of shorter pipes.

However we believe that, even in presence of more accurate measurements, a thourough analysis of the tuning of the flute cannot be based solely on acoustics, but needs to be informed with elements of theory of ancient Greek music. Melodic structures of this music are known [5, 9] to be based on the *tetrachord*, a series of four notes with the extremes tuned at a perfect fourth, i.e with a $4:3$ pitch ratio. While this interval is fixed, internal intervals can vary, giving rise to different *genera* of tetrachord. Each has variants, called *chroai* (shades), whose tunings comprise a large set of intervals, including 1/4-, 1/3-, and 7/6-tones. Two tetrachords can be linked together either by *synaphē* (conjunction), when the highest note of the first tetrachord coincides with the lowest of the second, or *diazeuxis* (disjunction), when there is a 1-tone interval between the two tetrachords. More complex structures (or *systems*) are derived by using more tetrachords. For example, a sequence of four tetrachords with the first-second and third-fourth in conjunction, and the second-third in disjunction, produces the *Greater Complete System* (see Fig. 8, where the relation between letters and tones is purely conventional and does not correspond to modern music notation system.).

More details about ancient Greek music are beyond the scope of this paper, but what is relevant here is that a particular system is characterized by a limited number of fixed pitches, corresponding to the outer notes of the tetrachords that compose the system, and tuned to a perfect fourth. Moreover, instruments were often tuned through a process called *lēpsis dia symphonias* (acquiring by concord) [9], i.e. by tuning in perfect fifths ($3:2$) and fourths ($4:3$),

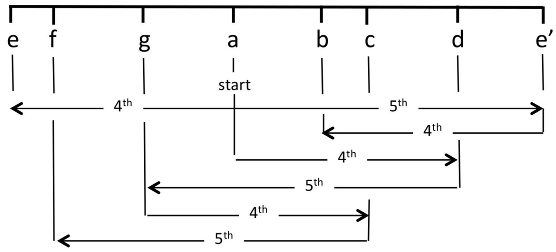


Figure 9. The "acquiring by concord" tuning method.

whereas tones were obtained by subtracting a fourth from a fifth, which correspond to a ratio of $9:8$ (see Fig. 9. Once more accurate estimates of pipe frequencies will be available, it will be possible to follow this method and search for $4:3$ and $3:2$ frequency ratios in order to reconstruct the tetrachord structure of the flute tuning.

4.2 An interactive multimedia installation

An important project outcome, from both the scientific and the dissemination viewpoints, is the realization of interactive applications that allow museum visitors to manipulate a virtual model of the flute, as well as to access historical and archaeological documentation about the instrument, such as photos, videos, and contextual information. A system composed of two applications is being designed.

The first application is an interactive multimedia installation allowing visitors to explore the artifact through the 3D model, since the original instrument is only weakly exposed to light for conservation purposes. The visitor controls the model with his hands (finger movements are tracked by an infrared sensor) while observing it on a monitor and, at the same time, playing the flute by blowing into a microphone. Furthermore, the visitor can choose different versions of the flute: the first based on the current state of the flute, the others based on virtual restaurations of the instrument that integrate the knowledge acquired during musicological and historical studies with the original model. By combining multimedia information about history of the ancient instrument with the musical practice, the installation is expected to provide an innovative and meaningful solution for informal learning.

In addition a mobile application will be freely downloadable by visitors on their own devices. Smartphones and tablets offer unprecedented multimedia and multisensory capabilities, being endowed with a wide range of sensors and input devices, and non-negligible computing power. Consequently mobile devices are finding significant applications in the virtual reconstruction of environments [10] and physical objects [11]. Apps for musical cultural heritage are a particularly interesting domain [12]. A mobile application with a skeuomorphic interface (i.e., one that leverages on the appearance and behavior of the physical artifact) is being designed: after the visit at the flute, visitors can study the history of the instrument and the music of its time from the installation described above, try to play some tunes handling the virtual model, and learn more complicated tunes studying on their own device, using it as a pan flute thanks to a *sensor fusion* approach that integrates data from the built-in camera, accelerometer and gyroscope to track movements and select the correct virtual pipe in front of the mouth. The microphone detects the attack envelope and the intensity of the breath.

5. CONCLUSIONS

The work presented in this paper is in its early stages. The main foreseen developments in the short term are a more refined analysis of the instrument tuning, which uses additional non-invasive measures (particularly CAT scan to estimate internal pipe lengths), and exploits elements of music theory of ancient Greek music as discussed in Sec. 4.1. The applications discussed in Sec. 4.2 are also under development and will be ready for visitors by summer 2016.

In the mid term we expect that the available data and results will fuel several further developments. One is sound synthesis of the pan flute by means of physical modeling approaches, to be integrated in the installations (which currently employ wavetable synthesis) in order to increase their interactivity. This is an interesting research topic *per se*, since to our knowledge there is only one previous study on sound synthesis of the pan flute in the literature [13].

A very high resolution 3D model may also be exploited for computationally intensive (i.e., based on finite differences or finite elements) approaches to acoustic simulations and sound synthesis, which have started to unveil their potential in recent years [14]. One further current research trend is 3D printing of musical instruments [15]: a "digitally restored" 3D model of the pan flute can be 3D printed and sensorized, thus becoming a tangible interface that recreates the physicality of the original instrument. A similar approach has been recently adopted by some of the authors for the case of electrophone instruments [16].

It is also worth mentioning that, since little is known about ancient greek music (and almost exclusively from treatises), such a well preserved instrument may serve as an important testbed for currently accepted theories. Even most importantly, we believe that, being the pan flute a primeval instrument which is widespread in different cultures worldwide, the impact of this research goes beyond this particular exemplary. The proposed "active preservation" approach developed for the project can be applied to other ancient and prehistoric musical instruments.

Acknowledgments

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6. REFERENCES

[1] F. Bressan and S. Canazza, "A systemic approach to the preservation of audio documents: Methodology and software tools," *Journal of Electrical and Computer Engineering*, vol. 2013, p. 21 pages, 2013.

[2] E. Cohen, "Preservation of audio in folk heritage collections in crisis," *Proceedings of Council on Library and Information Resources*, pp. 65–82, 2001.

[3] A. Menegazzi, M. Cesaretto, E. M. Ciampini, and P. Zanovello, "La scatola misteriosa," in *Egitto in Veneto*, P. Zanovello and E. M. Ciampini, Eds., Padova, 2013, pp. 91–104.

[4] C. Sachs, *The history of musical instruments*, 1st ed. W W Norton & Co Inc (Np), 1940.

[5] M. L. West, *Ancient Greek Music*. Oxford: Oxford University Press, 1992.

[6] N. H. Fletcher, "Stopped-pipe wind instruments: Acoustics of the panpipes," *J. Acoust. Soc. Am.*, vol. 117, no. 1, pp. 370–374, Jan. 2005.

[7] N. H. Fletcher and T. D. Rossing, *The physics of musical instruments*. New York: Springer-Verlag, 1991.

[8] E. Civallero, *Introducción a las flautas de pan*, 1st ed., Madrid, 2013, Creative Commons.

[9] J. G. Landels, *Music in ancient Greece and Rome*. Routledge, 1999.

[10] J. Thomas, R. Bashyal, S. Goldstein, and E. Suma, "Muvr: A multi-user virtual reality platform," in *Virtual Reality (VR), 2014 iEEE*, March 2014, pp. 115–116.

[11] M. Figueiredo, P. Cardoso, C. Goncalves, and J. Rodrigues, "Augmented reality and holograms for the visualization of mechanical engineering parts," in *Information Visualisation (IV), 2014 18th International Conference on*, July 2014, pp. 368–373.

[12] S. Canazza, C. Fantozzi, and N. Pretto, "Accessing tape music documents on mobile devices," *ACM Trans. Multimedia Comput. Commun. Appl.*, vol. Accepted for publication, 2015.

[13] A. Czyżewski, J. Jaroszuk, and B. Kostek, "Digital waveguide models of the panpipes," *Archives of Acoustics*, vol. 27, no. 4, pp. 303–317, 2002.

[14] S. Bilbao, B. Hamilton, A. Torin, C. Webb, P. Graham, A. Gray, K. Kavoussanakis, and J. Perry, "Large scale physical modeling sound synthesis," in *Proc. Stockholm Musical Acoustics Conf. (SMAC 2013)*, Stockholm, Aug. 2013, pp. 593–600.

[15] A. Zoran, "The 3d printed flute: Digital fabrication and design of musical instruments," *J. New Music Res.*, vol. 40, no. 4, pp. 379–387, 2011.

[16] F. Avanzini and S. Canazza, "Virtual analogue instruments: an approach to active preservation of the studio di fonologia musicale," in *The Studio di Fonologia - A Musical Journey*, M. Novati and J. Dack, Eds. Milano: Ricordi (MGB Hal Leonard), June 2012, pp. 89–108.