3D VIRTUAL RECONSTRUCTION AND SOUND SIMULATION OF OLD MUSICAL INSTRUMENTS

1. Introduction

For millennia, music culture has been handed down orally since the earliest detailed written music documents are relatively recent (Tomlinson 2012). Therefore, what we know about the music of the past is due to indirect documents, such as literature, music theory treatises, and iconography. In this context, archaeological finds of musical instruments such as ancient flutes or harps coming from ancient Egypt or Greek-Roman areas are a very important direct source of information. Unfortunately, these instruments are often seriously damaged and can no longer be played. Therefore, by observing these artifacts we can get an idea of the global shape and analyze the materials they are built from, but we can not listen to their sound and have experience of the performing practice.

Traditionally, playable copies of ancient instruments were built by craftsmen. This approach has several limits: a) the manufacturing process is usually slow and expensive; b) often one or few copies only can be built, limiting access to the instrument; c) when the reconstruction is uncertain, due to the poor state of conservation of the artifact, it is difficult to test and evaluate different possibilities.

Digital technologies based on 3D models overcome these limits. The reconstruction is virtual, therefore many different hypotheses can be tested; finite elements methods (Umetani *et al.* 2016) and physically informed algorithms allow to simulate the sounds produced by the artifacts, also giving a basis for evaluating the different reconstructions; virtual models can be easily shared, making possible global access to the heritage; finally, additive printing technologies offer the opportunity to have physical copies at relatively low costs. Nevertheless, methods and algorithms to obtain a virtual reconstruction of musical instruments in an automatic or semi-automatic way are still missing. Several algorithms were developed in the past years for simulating the sound of known instruments, but these algorithms need to be modified and improved to meet the requirements of these ancient and almost unknown instruments. 3D printing processes need to be tuned to consider the influence of materials and textures on sound generation.

2. Related work

The importance of music in particular, is a topic discussed broadly in literature (Sacks 2006; Bergh 2007; Storr 2015). Music, as a cultural activity

that can express and evoke emotions (Cooke 1959), is believed to be able to bind people and bring them together. «No culture so far discovered lacks music. Making music appears to be one of the fundamental activities of mankind» not only in present days but also in ancient times (Storr 2015). Thanks to the written music compositions handed down over the years and the specific details of the construction of the musical instruments, we can still nowadays arguably "hear" not only Bach's music but also, for instance, Mozart's and Beethoven's music the same way as the audience of their time. Furthermore, most of the places where they performed, along with some well-preserved musical instruments, dated back to their time, still exist today (Greilsamer, Freeman, Baker 1927). However, the same cannot be said about ancient music.

Although a good amount of ancient Roman and Greek musical artifacts have survived from antiquity, most of them are fragmentary and, for the most part, in no condition of being played. However, in order to better understand a musical instrument, it is very useful to listen to the sounds it produces (Pretto *et al.* 2020). The archaeology of music field focuses on excavating, identifying, classifying and ultimately reconstructing these ancient musical instruments (Van Keer 2010). Usually the first reconstruction is digital where a 3D model of the artifact is created. Making a 3D model opens many possibilities when it comes to analysing, simulating and recreating the lost sounds of the instrument, as well as creating a material copy of the instrument (Koumartzis *et al.* 2015). Afterwards, all efforts are aimed at further investigating the difference between the simulated sounds of the 3D model and the sounds produced by the physical replica. It is important to note that the materials constituting the instrument (including their provenance, treatment and workmanship), the playing posture and techniques, textual information as well as the location are all elements that need to be considered when simulating the sounds of the instrument (Both 2009). Therefore all the musical discoveries need to be evaluated in their archaeological and historical context, rather than in isolation (Bellia 2019). For example when reconstructing the Greek lyre of Hermes a tortoise-shell was used as a soundbox (Koumartzis *et al.* 2015).

There are several other reconstructions and sound simulations of ancient musical instrument. A fascinating case is the discovery in Sanzeno (Italy) of the remains of ancient Celtic musical artifacts known as *karnykes* (Roncador *et al.* 2014). These musical instruments were war trumpets that were used by the Celtic population to psychologically terrorize their enemies. Thanks to multiple international collaborations the historical and chronological context as well as the chemical and metallurgical properties of these musical artifacts have been studied. In 2011, to better understand the unique sounds produced by this instrument, a first prototype, made in brass, has been created. In addition to the case of the *karnykes* from Sanzeno, musical artifacts belonging to the same family have been excavated in Tintignac (France). Because the

karnykes from Tintignac were recovered in better conditions than the ones from Sanzeno, experts were able to put some of the parts together to make an almost complete authentic *karnyx*. Afterwards the virtual copy of the instrument was analyzed from an acoustic point of view to obtain data regarding its sounding characteristics. More specifically, several measurements concerning input impedance, resonance and playing frequencies have been made and the possible influence of the artifact's structure on the radiated sound was taken into consideration (GILBERT *et al.* 2012).

Another interesting example is the virtual and physical reconstruction (using polymer as the main material) of the *aulos* wind instrument found under Temple R at Selinunte and dated to 570 BCE (BELLIA 2019). This important discovery can help researchers better understand and investigate the ancient Greek music.

In general, not only small but also bigger organizations and museum institutions have been involved. The museum of Louvre-Lens has presented the first big exhibition *Musiques! Échos de l'Antiquité* dedicated to ancient musical instruments belonging to Greek, Roman and Egyptian ancient civilizations. Among these instruments, it is worth mentioning the case of the *cornua* of Pompeii. Five of these ancient wind instruments, belonging to the brass family, have been excavated and recovered in Pompeii, Naples. A virtual reconstruction of artifacts has been created and the sounds have been all modelled and synthesized with the help of the Naples National Archaeological Museum (EMERIT *et al.* 2017).

Another project that is important to mention is the European Music Archaeology Project (EMAP)[1], which has already reconstructed high-quality physical reproductions of more than 60 ancient musical instruments. Several exhibitions have been arranged where the public was able to touch and play some of these ancient instruments and experience past sound worlds and environments (DE ANGELI *et al.* 2018).

It is however important to note that, except for a few projects such as EMAP or Museo Interactivo de la Mùsica in Malaga (MIMMA)[2], not much has been done to promote and enhance these ancient musical instruments on the web. As we have seen, a certain number of research on sound simulation and virtual/physical reconstruction of ancient instruments exists, however, apart from the individuals involved in the research, most people do not have the possibility to listen to the fascinating music these musical artifacts can create. It is true that some of these researches have promoted these instruments through museum installations (BELLIA 2019; PRETTO *et al.* 2020); however,

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[1] http://www.emaproject.eu/ (retrieved May 5, 2021).
[2] http://www.musicaenaccion.com/mimma (retrieved May 5, 2021).

as discussed in the previous section, museums do not have the same appeal and the same potential to reach as many people as online websites can.

2.1 *Tuning and timbre*

Digital models are interesting because they allow us to have accurate measurements to simulate sounds, which is important to have evidence on the music of the time and to support hypotheses on the playing technique. Being able to listen to their sound and understand the methods of production allow us to have information on their use and role in society (FRITZ *et al.* 2021).

Among the many characteristics of a sound, the pitch is often considered the most important, at least from a musical point of view. Indeed, by knowing the set of pitches that can be generated by an ancient instrument, we can infer which structures of pitches (scales, modes, tetrachords, etc.) were used at that time. This is a very important aspect for many musical traditions, in particular for the ancient Greek-Roman music, where the analysis of coeval musical instruments can give evidences for a deeper understanding of the various historical theoretical treatises (see e.g. BARKER 2007) and support hypotheses related to the fine-tuning of those pitch structures (HAGEL 2009).

However, other aspects of the sound different from pitch are also interesting, such as intensity and timbre. To study these aspects, digital synthesis techniques offer many useful approaches. The sound produced by acoustic musical instruments is caused by the physical vibration of a resonating structure excited by a suitable action. It can be represented by a mathematical model and can be computed by synthesis algorithms (DE POLI 1983; BORIN *et al.* 1992).

If an existing reference instrument is available, it is possible to store in wavetables a large quantity of sound examples and during synthesis we just need to play one sound from the stored repertoire. Pitch transposition can be obtained by varying the speed when reproducing the sound. This technique (*sampling*) is characterized by high computational efficiency and high imitation quality, but by low flexibility for sounds not initially included in the repertoire or not easily obtainable with simple transformations.

Granular synthesis constructs complex acoustic events starting from a large quantity of elementary acoustic elements called grains. When the grains are irregularly distributed, we can obtain "clouds" of micro-sounds, or sonic textures, where the general statistical properties are more important than the exact sound evolution. In general, we can expect these types of sounds to occur in the real world when they are the result of multiple realizations of the same event or the same phenomenon. For example, among unpitched percussion, we find micro-sounds in the angled rainstick, (shaken) small bells, (grinding) ratchet, (scraped) guiro, (jingling) tambourine, and the many varieties of rattles.

Various instruments can be modelled as exciters, characterized by a rich spectrum, and a resonator (called filter) that transforms its spectrum. The

source-filter model allows to control and modify the fine (pitched or noisy) structure of the source separately from the spectral envelope of the filter. It is very effective for voice and resonating percussion instruments synthesis.

Physical modeling synthesis refers to sound modeling techniques in which the synthesis algorithms are designed based on a description of the physical phenomena involved in sound generation, in particular the physical objects and interactions that generate the sound. Among the different techniques, the *digital waveguide model* is particularly efficient for simulating flexible structures such as strings, cylindrical or conical tubes. This technique is based on the analytic solution of the equation that describes the propagation of waves in a medium and is realized with delay lines, junction elements, and filters. The structure and the parameters of the model can be derived from measurements of an actual artifact, but it is possible experiment the acoustic effects of structure and parameter variations, in correspondence of different reconstruction hypothesis.

3. Methodology

To build a digital model of a musical instrument, we can start from different sources: pictures, textual descriptions, technical drawings, and, of course, archaeological finds (Fig. 1). In the latter case, we need to measure these finds, by hand or, better, using recent techniques such as structured light scanners or computational tomography. From these techniques we can directly obtain a first rough 3D model of the instrument or the parts/fragments of it. By means of digital processing techniques, the instrument can be virtually restored. Interesting, we can obtain many different versions of the restored
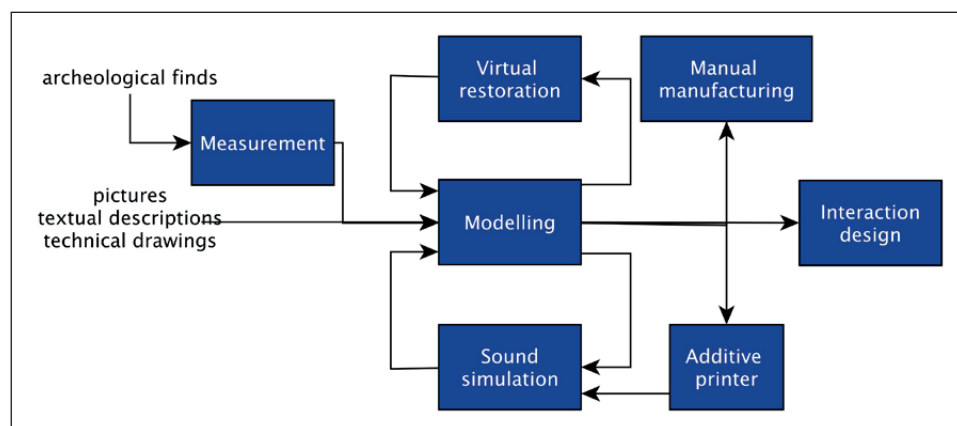

Fig. 1 – An iterative approach to the model of ancient musical instruments.

instrument, starting from different sets of hypotheses (about geometry, materials, missing parts, etc.) or addressing different objectives (e.g., to show the instrument as it is now or as it was originally).

From the restored model, we can then obtain a simulation of the sounds that could be produced by a musical instrument with such geometrical and functional properties. The generated sounds can also be used as a validation of the assumptions taken to build the model and can sometimes suggest further improvements to it.

The 3D model can also be used as a guide for a craftsman to construct physical copies of the instrument. Or, more easily, a physical version of the model can be directly obtained by an additive printer. In turn, following an iterative process, the physical copy can be used to estimate the parameters of the sound simulation algorithms more precisely.

Finally, the large amount of data and knowledge coming from this process, can be used to design novel approaches for enhancing the access to these instruments by scholars and the general public.

4. Case studies

The approach presented in Section 3 is exemplified through three case studies, differing in many aspects, the most relevant one is the state of conservation: the first study is a Pan flute in a good state, with 14 pipes mostly intact; the second is a brass musical instrument, quite damaged and broken in 8 more or less incomplete pieces; the last one is instead a lost instrument, of which we have only some technical drawings.

4.1 *Padova's Pan flute*

The first case presented in this paper is a well preserved ancient Pan flute, recovered in Egypt in the 1930s and currently exhibited in the Museum of Archaeological Sciences and Art (MSA) at the University of Padova (Fig. 2). Before being included in the permanent exhibit, the flute underwent a major restoration program for consolidation and (passive) preservation. Details about the history of the artifact, the place and circumstances of its recovery, as well as related literary and iconographic references in the Greek-Roman world, are provided in previous publications (Avanzini *et al.* 2015, 2016).

In comparison to similar findings, see e.g. the Pan flutes hosted at the Petri (Swift *et al.* 2021) and Louvre (Emerit *et al.* 2017) museums, this musical instrument is in a quite good state of conservation, with almost intact 14 pipes. The results of a radio-carbon analysis support the hypothesis that the flute dates back to the 7th c. CE.

From an acoustic point of view, the sounds of a Pan flute are generated by blowing inside the cavities of the pipes from the opened side of them. The
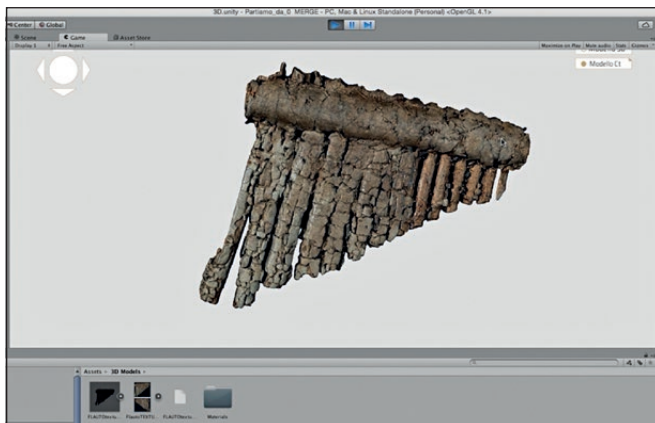
Fig. 2 – A view of the rendered 3D model of the Pan flute of Padova.

other end of the pipes is closed: in our case, the closures are obtained by means of the natural knots of the lake reeds that make up the instrument. Since the shape of the cavities of the reeds is well approximated by a cylinder with the length much greater than the diameter, the analytical solution of the wave equation is well known and allows to calculate the fundamental frequency of the sound produced by each pipe by means of the Eq 1:

$$f = \frac{4c}{l_{int} + \Delta l} Hz \qquad (1)$$

where c is the sound velocity, l_{int} is the internal pipe length, and $\Delta l = 0.305 d_{int}$ is the length correction at the open end, proportional to the internal pipe diameter d_{int} (FLETCHER, ROSSING 1991).

As shown by this equation, the estimation of the fundamental frequency requires the internal dimensions of each pipe. Since many pipes were full of residual dirt, which could not be removed to not compromise stability, a series of non-invasive analyses, based on 3D scanning using computed tomography (CT), have been performed (AVANZINI *et al.* 2016). Taking into account the inevitable measure errors, we estimated the possible range of the fundamental frequencies produced by each pipe (Table 1).

As previously stated, digital models of a musical instrument also allow us to simulate the sounds that such an instrument can produce. However, when we want to return the sounds from a so distant past, we must address the issues that we know very little about the way (e.g., the position and shape of the mouth in relation to the opened end of the pipe) those instruments were played, and which kind of music (i.e., sequences of pitches and rhythms)

pipe	f_{min} [Hz]	f_{max} [Hz]
1	638.7	649.7
2	677.2	700.7
3	753.6	773.5
4	843.1	874.4
5	928.3	974.7
6	1010.1	1041.3
7	1142.2	1184.3
8	1283.2	1346.4
9	1389.6	1438.2
10	1538.3	1602.0
11	1721.8	1758.1
12	1901.4	1957.3
13	2128.4	2205.1
14	2292.9	2499.7

Table 1 – Fundamental frequencies (min and max) estimated for each pipe starting from the measurements taken from the CT scan.

was used to be played, because no audio recordings exist and only very few fragments of written music (in some form of notation) arrived to us[3].

To get around these issues, we developed an interactive digital instrument that allows a user (musician, scholar, general public) to choose which notes to play and to control interactively some performance parameters such as the amplitude envelope (i.e., how the loudness of a sound varies in time). The user can play the instrument by using its blow, similar to an acoustic Pan flute: the flow of the blow is estimated by a sensor and its amplitude envelope is translated in messages of the MIDI protocol, namely *NoteOn* (attack), *ControlChange* (decay, sustain), and *NoteOff* (release), which control respectively the start, the time evolution, and the stop of the sound reproduction; then, these messages were sent to a sound synthesizer, specially developed on the base of a sampling approach (see Section 2.1).

The choice of this synthesis method for the Padova's Pan flute was guided by the following considerations: in comparison to other synthesis techniques it has a low computational cost, suitable for an interactive application; the Pan flute is a well-known instrument and it is easy to record or find audio samples of good quality; the main interest of this project was in rendering and studying the pitch patterns (musical scales, tetra-chords) generated by the instrument and the fine tuning of the tones, therefore a more refined simulation of the timbre was beyond its scope.

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[3] The study of musical practice also includes the agogic and dynamic aspects of the music performance (CANAZZA *et al.* 2015).

An interactive museum installation[4] for the instrument has also been designed and built. Thanks to this installation the visitors can hear the sounds of the Pan flute by physically blowing on specific holes, each having a microphone, located on a panel. This multimedia installation also provides the possibility of discovering the instrument's background and history as well as inspecting its 3D models (Avanzini *et al.* 2015, 2016). The creation of the installation was based on a carefully tuned multidisciplinary design approach centered on *Design Thinking* (Pretto *et al.* 2020).

4.2 *Voghenza's Roman brass*

The second case study is related to several pieces of metal, unequivocally recognized as a brass musical instrument, found in the context of the excavation of a Roman building in Voghenza, close to Ferrara (Italy), dated to the 2nd c. CE, and now hosted in the archaeological section of the Civic Museum of Belriguardo. This instrument is the subject of an ongoing multidisciplinary project[5], that aims to analyze, reconstruct, and valorize this important musical heritage.

The instrument, made of a metal alloy, is broken into 8 pieces, and each piece further suffers from large holes and damages. The 3D model of each piece was acquired by means of a structured light system that uses light patterns (or codes) and is based on digital cameras and projector. Models of the different pieces were subjected to two kinds of numerical elaboration. The first one aims to repair small holes and deformations by means of filters and numerical interpolation and is particularly suited for pieces with less severe damages. The second one aims to estimate the geometry of the entire instrument, by virtually reconnecting the pieces, also in case of very corrupted parts. In particular, an original algorithm was developed to estimate the central axis of the curved tube of the instrument and its increasing diameter (see Sun *et al.* 2020 for more details). Fig. 3 shows the estimated geometry (blue) of the entire instrument superposed to the original damaged pieces.

After the estimation of the geometry of the recomposed instrument, it is possible to simulate the set of tones that a musical instrument with that dimensions can produce. The mouthpiece, very similar to that of modern trumpets, trombones, and horns, reveals that the Voghenza's instrument certainly belongs to the brass family. The modalities of sound generation of these instruments are widely described in literature (e.g. Fletcher, Rossing 2012). The acoustic waves produced by the vibrating lips propagates through

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[4] Here you can see a video of the installation: https://youtu.be/P4yjw5R5qqY?t=165.

[5] The project currently involves the University of Padova (Dept. of Information Engineering and Cultural Heritage), the University of Bologna (Dept. of Cultural Heritage), the University of Salento (Dept. of Cultural Heritage), the Boston University (Dept. of Computer Science).
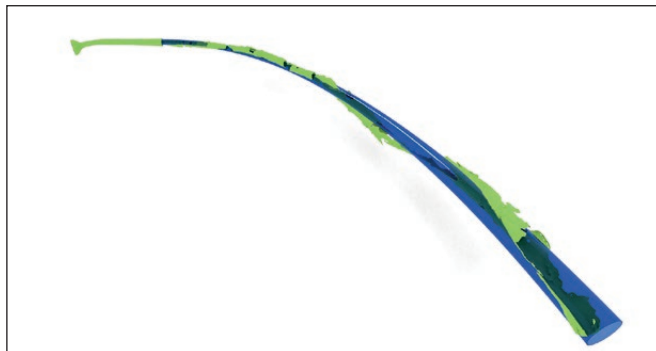
Fig. 3 – Aligned pieces from 3D scanning (green) and restored/rebuilt instrument (blue).

the cylindrical part of the instrument, the length of which can be modified in many brass instruments by means of holes (as in the cornetto), valves (as in the trumpet) or a sliding mechanism (as in the trombone). Then, the waves reach the ending flared section, where part of the acoustic energy is radiated to the outside of the instrument, and the rest part is reflected inside the bore.

From what we can observe from the remains, the Voghenza instrument has no holes, valves, or sliding parts. Therefore, the fundamental frequency of the tones depends largely on the peaks of the acoustic impedance of the bore. This impedance can be estimated analytically, starting from the well-known wave equation and solving it in the case of a wave propagating in a bore with increasing diameter. The solution lets to the following equation (CHAIGNE, KERGOMARD 2016) that allows the estimation of the frequencies f_n corresponding to a local maximum of the acoustic impedance:

$$f_n = \frac{c}{2(l + X_i)}\left[n - \frac{1 - v}{2}\right] Hz \qquad (2)$$

where c is the sound speed propagation, l is the length of the cylindrical part, X_i is the length of the flared part, v is a coefficient related to the shape of the flared part, and n is an integer number.

The unknown parameters of Eq. 2 were estimated by fitting the geometry of the reconstructed instrument (Fig. 3). Table 2 reports the frequencies of the natural resonances of the instrument estimated from Eq. 2. Finally, a sample of these sounds[6] were generated by a physically-informed algorithm based on a waveguide model (COOK 1991).

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[6] Examples of the sounds can be listen at: http://www.dei.unipd.it/~roda/brass/.

n	f_n [Hz]
1	123
2	266
3	409
4	553
5	696
6	839
7	982
8	1126
9	1269
10	1412

Table 2 – Natural resonant frequencies estimated from the geometry of the re-constructed 3D model of the instrument.

4.3 *Milan's* Studio di Fonologia Musicale

The last case study is a quite particular musical instrument, or better a set of instruments that were part of the *Studio di Fonologia Musicale* of Milan. Some of these instruments are no more existing, at least in their earliest form, but they are well documented by means of original technical drawings and pictures. During the 1950s and 1960s, this studio was one of the leading places in Europe to produce electro-acoustic music, together with Paris and Cologne. Although not ancient in a strict sense, these instruments can be considered as remarkable examples of industrial archaeology, due to its uniqueness and to the rapid evolution of the electronic technologies. Moreover, they represent the first steps towards the diffusion of musical electronic and digital devices that, in the following decades, radically changed the way of producing music and listening to it. The Studio (NOVATI 2009) was founded in 1955 at the Milan offices of the Italian Radio-Television (RAI), under the initiative of the Italian composers Luciano Berio and Bruno Maderna. In a few years, the Studio became one of the European centers of reference for the production of electroacoustic music, by deploying cutting-edge devices for the generation and processing of sound. These devices were especially designed and crafted by Alfredo Lietti: oscillators, filters, modulators, and other unique pieces, created with great care to meet the needs of the composers who attended the Studio. In 1967 the Studio underwent a partial renovation; as a consequence, much of the older equipment was dismantled and has been lost (RODÀ 2012). However, many photographs, diagrams, drawings, and audio recordings[7] were found in the archive of the Studio and thanks to these

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[7] Magnetic tapes containing the music works produced by using the electronic devices of the Studio. See BRESSAN *et al.* 2013 for aspects concerning the preservation of this type of documents.
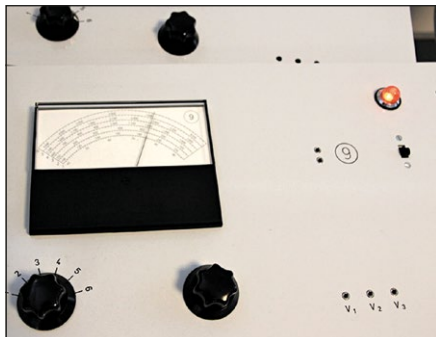
Fig. 4 – The replica of the control panel of one of the original oscillators of the Studio.
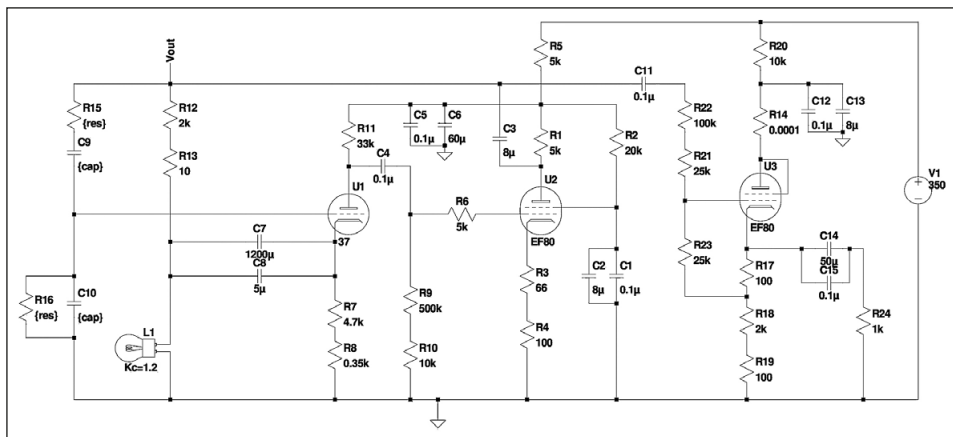

Fig. 5 – A transcription of the technical drawing of the oscillators designed by Alfredo Lietti for the Studio di Fonologia of Milan.

documents it is possible to know the characteristics and the functionality of most equipment that no longer exist. Electronic music instruments differ from traditional ones in many respects: the use of electric energy as the main sound producing mechanism, rapid obsolescence, the dependence on scientific research and available technology.

In 2011, the EU-funded DREAM project (NOVATI, DACK 2015) defined an approach to an active preservation of the electrophone instruments of the Studio, by following a multidisciplinary perspective that involved engineering, interaction design, and musicological competences. The project main outcome was to build a tangible copy of some of the electronic devices of the Studio, by

using digital simulation of the internal analog components and by replicating the physical appearance (Fig. 4).

The digital simulation of the sound generated by the devices was obtained by starting from their technical drawings. For example, Fig. 5 shows a transcription of the technical drawing of the oscillators designed by Alfredo Lietti for the Studio. Each electric and electronic component of this schema can be characterized by well known (because the single components were produced industrially) input-output functions, that was simulate numerically. By combining the function of the different components it is possible to simulate the output signal of the entire device (Avanzini, Canazza 2012). This approach is very similar to the physical modeling techniques (see Section 2.1) used to simulate the sound produced by acoustic instruments, with the difference that in this case we deal with electrical signals rather acoustic waves. Finally, a public installation was built and temporarily exhibited at the Music Instrument Museum in Milan; in this way visitors could feel the original experience of playing and producing electronic music (Canazza *et al.* 2011), by acting on switches and knobs[8].

5. Conclusions

Digital modeling techniques offer great opportunities for the study of musical instruments of antiquity, or even just no longer playable due to a precarious state of conservation or a rapid technological obsolescence. Of particular interest is the numerical simulation of the sounds those instruments could generate when they were in use: digital models allow us to generate and listen to those sounds, even if we have only a few fragmentary pieces of the instrument or just some descriptions or pictures. Although many sound modeling and simulation techniques are described in the literature, the choice of which one to use strongly depends on a) the state of conservation of the artifact (almost intact, strongly incomplete, no longer existing); b) its acoustic properties and the manner in which it is played (for example, percussion instruments are generally modeled differently from flutes or brass instruments); c) the aspects to be studied (musical structures, intonation, timbre); d) the access modalities that we want guarantee (e.g., only for scholars or accessible and playable by the general public). The case studies presented in this article offer three concrete examples of how and why these choices can be made.

What these projects showed us is that returning the sounds of instruments that are now silent is of great importance to support knowledge on the development of music and its function within the societies of the past. At the same time, specially from the point of view of museum curators, it represents

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[8] See https://youtu.be/7dxjJrmUMxA?t=260 for a demonstration of the digital simulation of some electronic devices of the Studio.

a great opportunity to bring this knowledge to the general public through a means (the sound) that is always very engaging, thanks to the emotional response that music and sound usually induce in the listener.

During the past decade, museums have embraced digital technology to enhance visitors' experiences. The use of digital technologies encourages museum visitors to actively engage with the artifacts. While respecting the original culture, technologies enable the development of new languages and experimentation by multiplying the narrations of the work. In this way, the visit to a museum becomes both educational and entertaining. Presenting artifacts to the general public is a complex task for their multifaceted nature, and digital technology must not sacrifice accuracy or depth of information for the sake of entertainment. Deploying digital technology is a multidisciplinary effort that requires interplay among different fields, from history and archaeology to information engineering and craftsmanship. A proper design methodology is necessary to draw the role of the artifacts of museums and galleries in the visitor experience.

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REFERENCES

Avanzini F., Canazza S. 2015, *Virtual analogue instruments: An approach to active preservation of the Studio di Fonologia Musicale*, in Novati, Dack 2015, 89-108.

Avanzini F., Canazza S., De Poli G., Fantozzi C., Micheloni E., Pretto N., Rodà A., Gasparotto S., Salemi G. 2016, *Virtual reconstruction of an ancient Greek Pan flute*, in *Proceedings of the 13th Sound and Music Computing Conference (SMC2016)*, 41-46 (https://doi.org/10.5281/zenodo.851179).

Avanzini F., Canazza S., De Poli G., Fantozzi C., Pretto N., Rodà A., Angelini I., Bettineschi C., Deotto G., Faresin E. *et al.* 2015, *Archaeology and virtual acoustics. A Pan flute from ancient Egypt*, in *Proceedings of the 12th International Conference in Sound and Music Computing (SMC 2015) (Maynooth 2015)*, 31-36 (https://doi.org/10.5281/zenodo.851067).

Barker A. 2007, *The Science of Harmonics in Classical Greece*, Cambridge, Cambridge University Press.

Bellia A. 2019, *Towards a new approach in the study of ancient Greek music: Virtual reconstruction of an ancient musical instrument*, «Digital Scholarship in the Humanities», 34, 2, 233-243 (https://doi.org/10.1093/llc/fqy043).

Bergh A. 2007, *I'd like to teach the world to sing: Music and conflict transformation*, «Musicae Scientiae», 11 (2 suppl.), 141-157.

Borin G., De Poli G., Sarti A. 1992, *Algorithms and structures for physical models synthesis*, «Computer Music Journal», 19, 4, 30-42.

Both A.A. 2009, *Music archaeology: Some methodological and theoretical considerations*, «Yearbook for Traditional Music», 41, 1-11.

Bressan F., Rodà A., Canazza S., Fontana F., Bertani R. 2013, *The safeguard of audio collections: A computer science based approach to quality control. The case of the sound archive of the Arena di Verona*, «Advances in Multimedia», ID 276354 (https://doi.org/10.1155/2013/276354).

Canazza S., Avanzini F., Novati M., Rodà A. 2011, *Active preservation of electrophone musical instruments. The case of the "Liettizzatore" of "Studio di Fonologia Musicale" (RAI, Milano)*, in *Proceedings of the 8th International Sound and Music Computing Conference (SMC 2011)*, 304-309 (https://doi.org/10.5281/zenodo.849867).

Canazza S., De Poli G., Rodà A. 2015, *CaRo 2.0: An interactive system for expressive music rendering*, «Advances in Human-Computer Interaction», ID 850474 (https://doi.org/10.1155/2015/850474).

Chaigne A., Kergomard J. 2016, *Acoustics of Musical Instruments*, New York, Springer.

Cook P. 1991, *Tbone: An interactive waveguide brass instrument synthesis workbench for the NeXT machine*, in *Proceedings of the 1991 International Computer Music Conference, ICMC 1991 (Montreal 1991)*, 297-299 (https://dblp.org/rec/conf/icmc/HirschmanCS91).

Cooke D. 1959, *The Language of Music*, Oxford, Oxford University Press.

De Angeli S., Both A., Hagel S., Holmes P., Jiménez Pasalodos R., Lund C. (eds.) 2018, *Music and Sound in Ancient Europe: Contributions from the European Music Archaeology Project*, European Music Archaeology Project.

De Poli G. 1983, *A tutorial on digital sound synthesis techniques*, «Computer Music Journal», 7, 4, 8-26.

Emerit S., Guichard H., Jeammet V., Perrot S., Thomas A., Vendries C., Vincent A., Ziegler N. 2017, *Musiques! Échos de l'Antiquité*, Gent, Snoeck Publishers.

Fletcher N.H., Rossing T.D. 1991, *The Physics of Musical Instruments*, New York, Springer Verlag.

Fletcher N.H., Rossing T.D. 2012, *The Physics of Musical Instruments*, Springer Science & Business Media.

Fritz C., Tosello G., Fleury G., Kasarhérou E., Walter P., Duranthon F., Gaillard P., Tardieu J. 2021, *First record of the sound produced by the oldest Upper Paleolithic seashell horn*, «Science Advances», 7, 7 (https://doi.org/10.1126/sciadv.abe9510).

Gilbert J., Brasseur E., Dalmont J.-P., Maniquet C. 2012, *Acoustical evaluation of the Carnyx of Tintignac*, in *Proceedings of Acoustics 2012 (Fremantle 2012)*, 3956-3959.

Greilsamer L., Freeman J.C., Baker T. 1927, *On old violins*, «The Musical Quarterly», 13, 3, 410-433.

Hagel S. 2009, *Ancient Greek Music: A New Technical History*, Cambridge, Cambridge University Press.

Koumartzis N., Tzetzis D., Kyratsis P., Kotsakis R. 2015, *A new music instrument from ancient times: Modern reconstruction of the Greek lyre of Hermes using 3D laser scanning, advanced computer aided design and audio analysis*, «Journal of New Music Research», 44, 4, 324-346.

Novati M.M. (ed.) 2009, *Lo Studio di Fonologia. Un diario musicale 1954-1983*, Milano, BMG Ricordi Publications.

Novati M.M., Dack J. (eds.) 2015, *The Studio di Fonologia: A Musical Journey 1954-1983, Update 2008-2012*, Milano, BMG Ricordi Publications.

Pretto N., Micheloni E., Gasparotto S., Fantozzi C., De Poli G., Canazza S. 2020, *Technology-enhanced interaction with cultural heritage: An ancient Pan flute from Egypt*, «Journal on Computing and Cultural Heritage», 13, 2, 267-280 (https://doi.org/10.1145/3355395).

Rauterberg M. (ed.), *Culture and Computing. HCII 2020*, Lecture Notes in Computer Science, 12215, Cham, Springer (https://doi.org/10.1007/978-3-030-50267-6_21).

Rodà A. 2012, *Evolution of the equipments of the Studio di Fonologia Musicale of Milan*, in Novati, Dack 2015, 33-81.

Roncador R., Bellintani P., Silvestri E., Ervas A., Piccardo P., Mille B. 2014, *Karnykes a Sanzeno: dalla riscoperta alla ricostruzione sperimentale*, in *Les Celtes et le Nord de l'Italie. Premier et Second Âges du Fer, Actes du XXXVIᵉ Colloque International de l'AFEAF (Vérone 2012)*, «Revue Archéologique de l'Est», Suppl. 36, 667-678.

Sacks O. 2006, *The power of music*, «Brain», 129, 10, 2528-2532.

Storr A. 2015, *Music and the Mind*, New York, Simon and Schuster.

Sun Z., Rodà A., Whiting E., Faresin E., Salemi G. 2020, *3D virtual reconstruction and sound simulation of an ancient Roman brass musical instrument*, in C. Stephanidis (ed.), *Human-Computer Interaction - HCI International 2020 (Copenhagen 2020)*, Springer, 267-280.

Swift E., Bosworth L., Creese D., Morris G., Pudsey A., Richardson J., Stoner J., Walker F., Wright G. 2021, *Creation of functional replica Roman and Late Antique musical instruments through 3D scanning and printing technology, and their use in research and museum education*, «Internet Archaeology», 56 (https://doi.org/10.11141/ia.56.1).

Tomlinson G. 2012, *Musicology, anthropology, history*, in M. Clayton, T. Herbert, R. Middleton (eds.), *The Cultural Study of Music*, New York, Routledge, 81-94.

Umetani N., Panotopoulou A., Schmidt R., Whiting E. 2016, *Printone: Interactive resonance simulation for free-form print-wind instrument design*, «ACM Transactions on Graphics», 35, 6, 1-14.

Van Keer E. 2010, *Archaeology of ancient Greek music: From reconstructing instruments to deconstructing concepts*, «Studies in Music Archaeology», 7, 43-51.

ABSTRACT

Digital technologies and 3D models, nowadays largely used to document archaeological remains and to obtain hypothetical reconstructions when these remains are more or less heavily damaged, can also be powerful tools to simulate and render the acoustic response of an environment, such as the interior of a building, or an artifact, such as sounding objects or musical instruments. This work addresses the cases of three musical instruments of the past – namely a Pan flute, a brass instrument, and an electrophone instrument – coming from different periods and in different states of preservation, which voices can now be heard thanks to as many multidisciplinary projects. Possible approaches to the simulation of the sounds that these instruments could generate are discussed in relation to different aims and contexts.