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AUGMENTATION AND ENRICHMENT OF CULTURAL EXHIBITS VIA DIGITAL INTERACTIVE SOUND RECONSTRUCTION OF ANCIENT GREEK MUSICAL INSTRUMENTS

1. Introduction

A significant number of Ancient Musical Instruments (AMIs) findings, which date from the 5th c. BCE to the 1st c. BCE, are kept in various archaeological museums in Greece and all over the world. Some of them are in good condition. Some of the most important AMIs are exhibited at the Archaeological Museum of Piraeus (Psaroudakēs 2013a): from the classical era a flute (Psaroudakēs 2013b), a chelys (a type of lyre), and a *trigonon* (a type of harp) (Terzēs 2013), and at the Archaeological Museums of Megara (Terzēs 2020): from the Hellenistic period two pairs of *aulos* with metal sliding keys. Some of the excavated AMIs have been studied by expert archaeomusicologists who emphasized their functional restoration and reconstruction (Bellia 2015; Safa *et al.* 2016). Indirect but valuable information about the musical instruments of Greek antiquity can be found in ancient Greek literature (the surviving texts of ancient Greek authors) and the musical iconography (representations of musical instruments on vases, painted or embossed works). The research results on ancient Greek music have increased exponentially in the last twenty years (Pöhlmann, West 2001; Hagel 2009a), and that is mainly due to the development of archaeomusicology and the recently excavated AMIs (Psaroudakēs 2000, 2002, 2008, 2010, 2013a; Hagel 2004, 2008; Terzēs 2013, 2020).

According to recent studies (Kurke 2000; Murray, Wilson 2004), organized sound (music and song) was the main factor that formed the ancient Greek intellectual and artistic product (epic, choral/lyric poetry, drama, comedy). However, even nowadays, there are not enough studies regarding the sonification of the AMIs to cover the majority of the excavated instruments, and therefore, the museum visitor cannot hear the actual sound of an exhibited instrument. On the other hand, their visual representation is widespread (a large volume of digitized illustrations is available). Despite the fact that recent technology is put in practice and remarkable progress has been done (i.e., digitization of the cultural apparatus, development of on line museum tours and digital guides based on mobile devices, such as tablets or smartphones), the reconstruction of the AMIs sound is still not available, except Avanzini's individual project (Avanzini *et al.* 2015).

The reconstruction of AMIs via physical apparatus (replicas), through interdisciplinary study and research (musicology and archaeology), provides satisfactory results. Nevertheless, as it is usually approached by trial and error techniques, it requires disproportional effort, which increases the construction cost (Hagel 2009b; Psaroudakēs 2013a; Koumartzis *et al.* 2015). A similar problem is present in the construction of traditional instruments, especially in the process of standardization and optimization. The introduction of playable reconstructed musical instruments in the museums (as is the case with any object that contains elements of ancient technology) is not considered appropriate, and it is not adopted because: a) of aesthetic arrangement issues of the exhibition space, b) of noise disturbance issues when used by a visitor, c) the generated sound is not representative especially in the case of AMIs made of animal bones (Safa *et al.* 2016), and d) of provided grounds for anachronistic interpretations that may hurt the exhibited instrument. We here propose an enriched museum experience where the visitor sees the original AMI and at the same time interacts with its digital simulation through a tablet, a digital kiosk, or a mobile device (either by altering some of its features or by playing notes) and hears the generated sound (on headphones) in real-time. Moreover, this application will help the scientists (i.e., archaeomusicologists) to study the AMIs as it provides flexibility in modifying the instruments' parameters (e.g., geometrical features) and swiftly obtaining the relevant sound. This is a powerful tool that will speed up the musicological study of the AMIs, by enabling a fast and accurate scale estimation. Furthermore: a) our method can be combined with recent methods that take into account the musician's interaction with the instrument to optimally tune the set of generated fundamentals (Bakogiannis *et al.* 2020), b) our method's output signals can then be filtered with a digital filter which simulates the acoustics of various ancient theatres to obtain their sound in their natural auditory space (Vassilantonopoulos, Mourjopoulos 2003; Polychronopoulos *et al.* 2013), and c) the instrument's introduced geometry can be treated as an acoustic metamaterial (Polychronopoulos, Memoli 2020) enabling the 3D printing of a functional (in some instrument classes) musical instrument (Noreland *et al.* 2013).

In the last two decades, the synthesis of the sound of musical instruments using the method of physical modeling (Eckel 1995) has received increasing attention in the field of music technology. This method is based on the description of the production and propagation mechanisms of sound using mathematical models that describe the acoustics of sound production. It embodies the Newtonian ideal of an exact mathematical model of a mechanical-acoustic process (Roads, Strawn 1996). Unlike the rest of the simulation methods, it does not require instrument recordings in order to build a model, which is a rather significant advantage in some cases (i.e., in the case of an excavated ancient musical instrument where it is fragile or/and not in one piece).

For the creation of the virtual musical instruments and their use during the performance, the physical modeling method is going to be used as it provides not only more realistic but also more expressive synthetic sound (Välimäki, Takala 1996; Aramaki *et al.* 2001; Rabenstein, Trautmann 2001). The usual methods of sound synthesis (FM, additive, subtractive, AM, PD, Granular: Miranda 2002) try to reproduce the spectral content of the acoustic signal produced by a musical instrument, but their parameters are not related to the instrument's physical parameters. Moreover, all the other methods, for example, the widely used and computationally cheap method of sampling (reproduction of recorded samples from the physical instrument), require the existence of the instrument. This is a major constrain when the instruments in question are excavated, thus, fragile and usually not in one piece. On the contrary, the physical modeling method does not produce the sound directly but produces and controls the process that creates the sound (Serafin, Smith 2000). The main approaches of this methodology include the digital waveguide (Välimäki, Savioja 2000), the transfer function model (Borin, De Poli, Sarti 1992), the modal synthesis (Bisnovatyi 2000), and the finite differences using resonant filters (Bilbao 2009). Furthermore, approaches for the physical modeling of double-reed musical instruments have been presented in the literature (Erkut, Karjalainen 2002; Bilbao, Smith 2003; Karjalainen, Erkut 2004; Bensa *et al.* 2005).

The Virtual Musical Instrument (VMI) is a credible (as much as possible) digital representation of the corresponding real one and consists of two distinct parts (Tzevelekos, Georgaki, Kouroupetroglou 2008). The first is responsible for the audio reconstitution of the produced sound in real-time, and we call it Acoustic Virtual Musical Instrument (AVMI) and the second one is the Visual Representation, which is usually a realistic three-dimensional representation. The most promising simulation method of AMIs is based on physical modeling algorithms that solve the system of equations that corresponds to the acoustics of the real musical instrument (Välimäki V, Takala 1996). A digitally simulated AMI has to produce a sound as similar as possible to the sound that the corresponding musical instrument makes and, moreover, to enable the ability to interact with it through an external physical apparatus. Nevertheless, there are no strict directions and autonomous frameworks for the development of AVMIs. Most of the relevant applications are limited (closed and non-scalable systems) and do not combine their visual representation as the user interacts with them (i.e., playing music). They are not easy to use and not suitable for non-specialists (e.g., museologists, archaeologists) as they cannot modify them or develop their own digital AMI based on specific requirements (e.g., to accurately reproduce the sound of a specific exhibited AMI). In this work we show the simulation method of the AMIs and propose a flexible and scalable digital tool through which: i) the museum's scientific staff will be able to create an AVMI that will accurately reproduce the sound of a specific AMI and ii) the experience of each *in situ* or online visitor of the museums will be enriched and enhanced with the digitally generated sound (by every single digital AMI) along with its three-dimensional representation, but will also enable the real-time interaction to produce music.

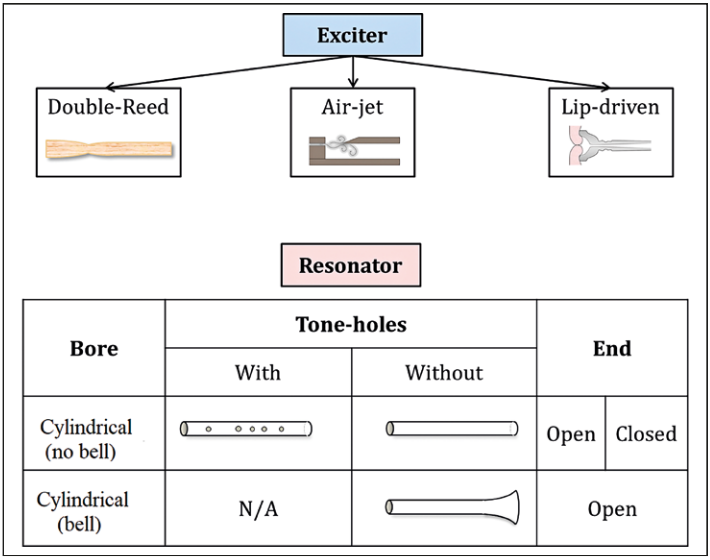
2. Methods

In this section, we discuss the simulation of wind AMIs (classes: *Aulos*, *Plagiaulos*, *Syrinx*, and *Salpinx*) and the simulation of string AMIs (classes: *Phorminx*, *Chelys*, *Barbitos*, *Kithara*, and *Trigonon*).

Digital waveguides were used to simulate the wind AMIs. Due to the complex shape of their body and material properties, the string AMIs are simulated using a hybrid method. We used Digital Signal Processing (DSP) and, more precisely, digital waveguides to simulate the vibrating string (Askenfelt, Jansson 1993; Fletcher, Rossing 1998; Giordano, Gould, Tobochnik 1998; Rossing 2010; Perov, Johnson, Perova-Mello 2016) and Finite Element Method (FEM) to simulate the vibrating body of the instrument (Richardson, Roberts 1985; Karjalainen, Smith 1996; Carlson 1996; Stanciu, Vlase, Marin 2019). Through this hybrid (DSP-FEM) method, the overall sound production mechanism is modeled, and the sound produced by the musical instrument is approximated.

2.1 *Wind instruments*

Not all wind instruments share the same type of excitation mechanism (sound generator). The classes of wind AMIs this project is taking into account have three different types. The first one is the reed instruments, where the exciter includes the dynamics of reed vibration and air flowing through a reed aperture. Initially, the reed is at rest, where the pressure difference (between the mouth pressure and the pressure inside the reed) equals zero, and the reed's opening area is at its maximum level. While they slowly increase the pressure, the blades are closing progressively. When the pressure difference exceeds a certain value, the reed is forced to shut rapidly (Almeida, Vergez, Caussé 2004). The second is the air-jet-driven instruments, where the excitation mechanism is described by the air jet deflected. The acoustic oscillation inside the resonator creates an oscillating transversal flow through the embouchure hole, which perturbs the jet's trajectory (Carpenter 2012; Fabre, Gilbert, Hirschberg 2018) at the flow separation point. Because of the unstable nature of air jets, this perturbation travels and gets instinctively amplified along with the jet. The required acoustic energy to sustain the air particles' oscillation inside the resonator is provided by the interaction of the perturbed flow with the labium (De La Cuadra 2006). The perturbed flow



Bore	Tone-holes		End	
	With	Without		
Cylindrical (no bell)			Open	Closed
Cylindrical (bell)	N/A		Open	

Fig. 1 – Three types of excitation mechanisms: Double-reed (*Aulos*), Air-jet instrument (*Plagiaulos* and *Syrinx*), and Lip-driven (*Salpinx*). Resonator types with various geometries, with (*Aulos* and *Plagiaulos*) and without tone-holes (*Syrinx* and *Salpinx*), with open (*Aulos*, *Plagiaulos*, and *Salpinx*) or closed (*Syrinx*) end for and the cylindrical bore without a conical bell (*Aulos*, *Plagiaulos*, and *Syrinx*) and with a conical bell (*Salpinx*).

is amplified until it reaches a side displacement which prevents its form from being cohesive and results in the reformation of the air jet. The behavior of the air jet inside a flue instrument is a non-linear phenomenon. This non-linearity is due to the fact that, even though the jet grows linearly at first, when it interacts with the perturbed flow, it breaks into vortices that conclude into turbulence (Carpenter 2012).

The third one is the lip-driven generator mechanism. There is an important difference between this type of excitation mechanism and the aforementioned two types, which mainly arises from the fact that the blowing pressure tends to force the player's lips open, while in woodwinds, it tends to force the reed closed. It should be noted here that, in this mechanism, the lips are the equivalent to the vibrating reed.

Fig. 1 shows the exciter types that will be discussed here as they are relevant to the exciter mechanisms of the instruments this work is focusing on. More precisely the exciter types of the AMIs we simulated are: Double reed (*Aulos*) (Almeida, Vergez, Caussé 2004, 2007), Air-jet (*Plagiaulos* and *Syrinx*) (Chanaud 1970; Fletcher, Rossing 1998; Auvray, Fabre 2016; Fabre, Gilbert, Hirschberg 2018), and Lip-driven (*Salpinx*)

(Benade 1990). The various resonator types are also shown in Fig. 1; with (*Aulos* and *Plagiaulos*) and without tone-holes (*Syrinx* and *Salpinx*), with open (*Aulos*, *Plagiaulos*, and *Salpinx*) or closed (*Syrinx*) end and the cylindrical bore without a conical bell (*Aulos*, *Plagiaulos*, and *Syrinx*) and with a conical bell (*Salpinx*). The cylindrical bore of the *Aulos*, *Plagiaulos*, and *Syrinx* was modeled as a one-dimensional digital waveguide, i.e., as two delay lines, one for the left and one for the right going wave, as the theory of digital waveguides describes (Scavone 1997; Czyżewski, Jaroszuk, Kostek 2002; Smith 2002; Scavone 2018). Concerning the excitation mechanism, in the case of *Aulos*, a reflection coefficient factor is used (due to the reed mechanism) (Smith 2002, Polychronopoulos et al. 2021), while in the case of *Plagiaulos* and *Syrinx*, the sigmoid function is used to simulate the air-jet excitation mechanism (Cook 1992), and in the case of *Salpinx* the lip oscillation is simulated as a mass-spring-damper oscillator (Cook 1991). The open and close ends were simulated by digital filters according to the frequency-dependent transmittance and reflectance happening in each type of ending. The reflection and transmission characteristics of the *Salpinx* bell are implemented by using lumped filters (Berners 1999) in combination with the waveguide model of the instrument. According to Smith 2004a, the reflectance of the travelling waves due to the bell of a woodwind instrument is commonly modeled as a low-pass filter, while the transmittance is implemented as a complementary high-pass filter. The modeling methods described above simulate the basic mechanisms and factors of the wind instruments' sound generation, in particular, the bore's geometry (length, inner and outer diameters), the bore's ending type (open/closed), the bore's shape (cylindrical/ conical), the tone-holes (number, position, and dimensions/ geometry), and the excitation mechanisms (reed driven, air jet, and lip driven). Our models can be further expanded to enable additional simulation parameters, such as the player's subtle control of the sound quality (e.g., vibrato and transients), type of flaring, and the mouthpiece effect, and can be further tuned to produce more realistic outcomes (Bakogiannis *et al.* 2021).

The fundamental note (frequency) created in the resonator depends on the length of the resonator and whether the end of it is closed or open. As a simplified practice, one can assume that, by opening a tone-hole, the effective length of the resonator reduces and, therefore, the fundamental frequency generated is higher. For an open-end, the wavelength of the fundamental frequency is approximately twice the length of the pipe, and for a closed-end the wavelength is approximately four times the length of the pipe (Wolfe 2018). In the final application the user sets the parameters' values for each AVMI (see Figs. 3 and 4) and both wind or string instrument physical models run in the time domain to synthesize the relevant audio signal and plot its spectrum in the frequency domain through the Fast Fourier Transform.

2.2 *String instruments*

DSP using Digital Wave Guides (DWG) and FEM solving in Time Domain are the two most commonly used physical modeling techniques. The DSP method is more commonly used than the FEM mainly because it is less computationally demanding. Therefore, in order for the algorithm to be able to respond and play the sound of an instrument in real-time, the DSP method is more suitable. The vibration of string musical instruments can be simulated as 1D DWG. However, the vibrating body of the instrument, which is the main sound source due to its complicated geometry, cannot be simulated with the same computationally cheap method. Julius Smith published an article comparing the effectiveness of DWG and Finite Difference Time Domain (FDTD)

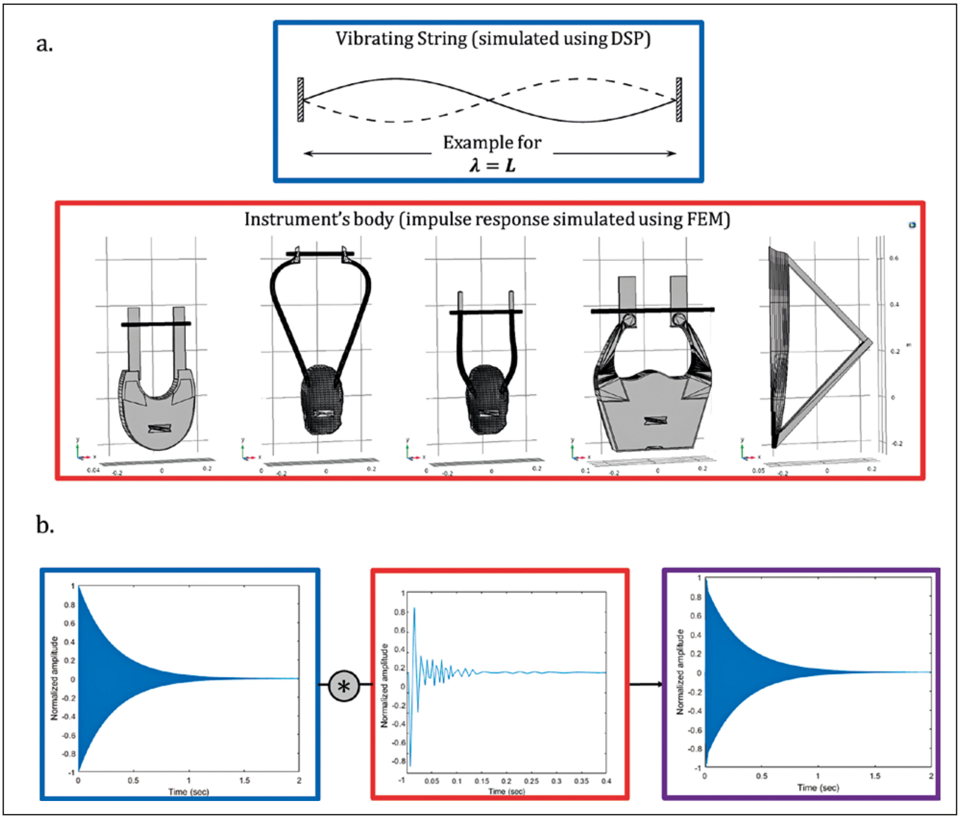
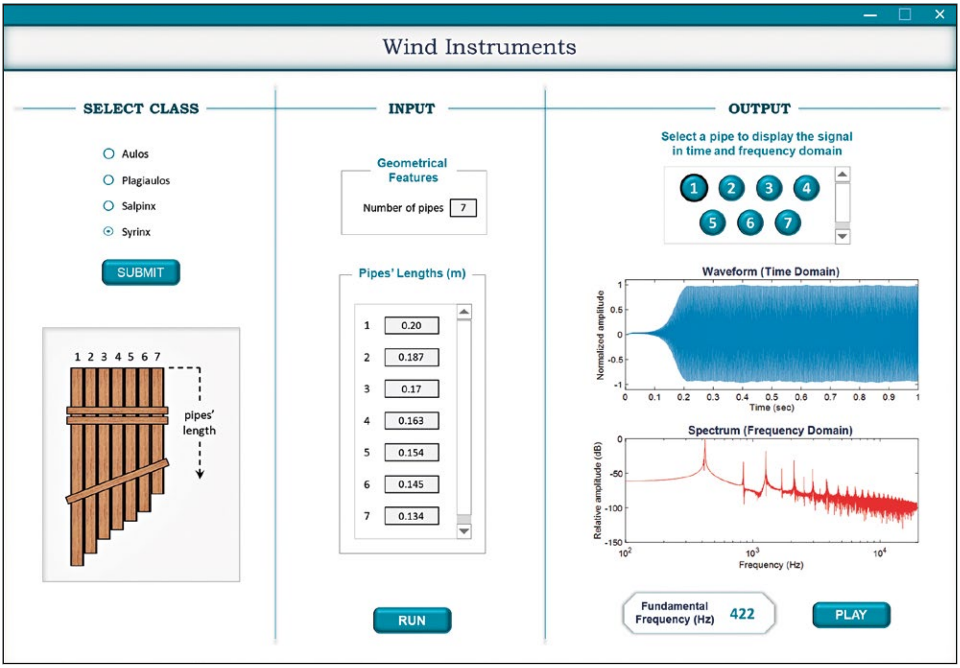


Fig. 2 – a) blue frame: the vibrating string; red frame: the 3D of the body of the instruments (*Phorminx*, *Chelys*, *Barbitos*, *Kithara*, and *Trigonon*) in COMSOL Multiphysics 5.5. b) blue frame: the signal from a vibrating string (string's length = 0.36 m, Tension = 32.85 N, Linear Density = 0.0005832 kg/m) simulated using DPS (digital waveguides); red frame: the impulse response of the body of the instrument (*Trigonon*) using FEM; purple frame: their convolution.

(Smith 2004b). Our FEM model used to simulate the body's vibrations through the calculation of its impulse response shares common principles with FDTD as it runs in the Time Domain in order to calculate the impulse response of the system. After Smith's work, more works followed (Erkut, Karjalainen 2002; Bilbao, Smith 2003; Bensa *et al.* 2005). Cumhur Erkut and Matti Karjalainen came up with an approach combining the two models for the simulation of string instruments (Erkut, Karjalainen 2002). Additional work was published 2 years later by the same authors with a more generalized approach proposing a renewed hybrid model (Karjalainen, Erkut 2004).

In this work, in order to encounter the complicated geometry of the body of the string instruments, a hybrid method was used. The signal from the vibrating string (DSP-DWGs) is convoluted with the impulse response of the body of the instrument (FEM – solving in Time Domain) for our hybrid model to output the final audio signal of the wind AMI (Karjalainen, Välimäki, Jánosy 1993; Karjalainen, Smith 1996) (Fig. 2). The complete study of the sound produced must include, in addition to the distinct study of the string and the body, the role of the bridge. The frequency response of the body is obtained by exciting the bridge at different frequencies (Rossing 2010). In low frequencies, there is a better agreement between the produced sound and the excitation than in high frequencies. This is due to the fact that the directionality can vary as a function of eigenfrequency, as well as the fact that a small movement of the bridge does not automatically imply a high level of sound production. More precisely, the body of the string musical instrument functions as a linear mechanical-acoustical system, which transforms the forces imposed by the vibration of the string into sound pressure waves propagating in the air.

As the calculation of the impulse response in FEM requires some time, we here propose two application types: a) the impulse response of all the AMIs exhibited in the museum is pre-calculated in order for the visitor to be able to interact with the digital instrument in real-time altering only the strings' parameters and b) the user is able to upload the 3D geometry of the body of the instrument and parameterize the strings as well. The first application type runs in real-time, and it is better for commercial use, while the second one provides more freedom in the design and it is more research-oriented. In case the string AMI, found in the excavation, is in one piece, its geometry can be easily obtained by using a 3D scanner. If there are missing parts, the archaeologist can digitally design various possible versions of the instrument's body and study each version's results. Moreover, the digital calculation of the impulse response does not require a physical measurement (which is not possible since AMIs are fragile and the impact could destroy them), enabling the researchers to test their assumptions regarding unknown parameters of the soundboxes, even when there are no actual remains of the instruments (for instance, in the case of *kitharas* or *phorminx*).



Wind Instruments

SELECT CLASS

○ Aulos
○ Plagiaulos
○ Salpinx
● Syrinx

INPUT

Geometrical Features

Number of pipes: 7

Pipes' Lengths (m)

1	0.20
2	0.187
3	0.17
4	0.163
5	0.154
6	0.145
7	0.134

OUTPUT

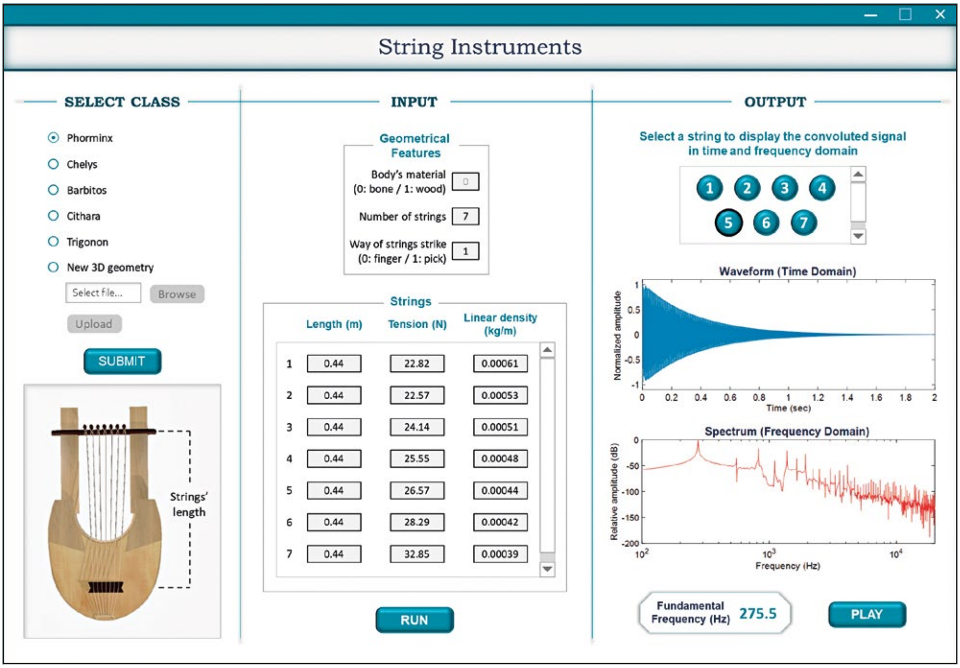
Select a pipe to display the signal in time and frequency domain

Fundamental Frequency (Hz): 422

Fig. 3 – The Graphical User Interface of the wind instruments. The user can select between instrument classes (*Aulos*, *Plagiaulos*, *Syrinx*, and *Salpinx*) and the relevant parameters. In the example shown here, the *Syrinx* class is selected and the parameters are shown. The generated signal in time and frequency domain as well as the fundamental frequency, are calculated right after the user hits the run button. After the calculation is completed, the user selects the desirable pipe and the relevant plots are illustrated on the right part of the GUI. The audible stimulus occurs by hitting the play button.

3. APPLICATION

We here demonstrate the Graphical User Interface for the project's wind (Fig. 3) and string (Fig. 4) instruments. The user can select between the instrument classes of a wind (*Aulos*, *Plagiaulos*, *Syrinx*, and *Salpinx*) or a string (*Phorminx*, *Chelys*, *Barbitos*, *Kithara*, and *Trigonon*) instrument. We would like to note here that due to the way we are simulating the body of the string instruments we provide the option for the user to add a 3D geometry, which is giving extra flexibility considering that small differences in the body of the instrument will significantly affect the generated signal. Then, a set of parameters show up as illustrated in Fig. 3 and Fig. 4 in the input section. We narrowed down the allowed parameters' values to be between low and high extreme values (within logical limits, e.g., two tone-holes cannot be at the same position). This is mandatory firstly for the algorithm to be able to



● Phorminx
○ Chelys
○ Barbitos
○ Cithara
○ Trigonon
○ New 3D geometry

Geometrical Features

Body's material (0: bone / 1: wood) 0
Number of strings 7
Way of strings strike (0: finger / 1: pick) 1

Strings

	Length (m)	Tension (N)	Linear density (kg/m)
1	0.44	22.82	0.00061
2	0.44	22.57	0.00053
3	0.44	24.14	0.00051
4	0.44	25.55	0.00048
5	0.44	26.57	0.00044
6	0.44	28.29	0.00042
7	0.44	32.85	0.00039

Fundamental Frequency (Hz) 275.5

Fig. 4 – The Graphical User Interface of the string instruments. The user can select between instrument classes (*Phorminx*, *Chelys*, *Barbitos*, *Kithara*, and *Trigonon*) and the relevant parameters. In the example shown here, *Phorminx* class is selected and the parameters are shown. The generated signal in time and frequency domain, as well as the fundamental frequency, are calculated right after the user hits the run button. After the calculation is completed, the user selects the desirable string and the relevant plots are illustrated on the right part of the GUI. The audible stimulus occurs by hitting the play button.

run the calculations (e.g., not acceptable parameter number of strings = 0) and secondly for the results to make sense (e.g., not acceptable 50 m long string as it does not make sense for an AMI). In the examples shown in Fig. 3 and Fig. 4, *Syrinx* and *Phorminx* classes are selected, and the relative parameters are shown. The generated signal in the time and the frequency domain, as well as the fundamental frequency, are calculated right after the user hits the run button. After the calculation is completed, the user selects the desirable option (e.g., pipe in the case of the syrinx in the example of Fig. 3 or string in the case of any string instrument), and the relevant plots are illustrated on the right part of the GUI. The audible stimulus occurs by hitting the play button.

This application will be useful not only to scientists but to a broader audience as well. The first category is mainly the scientific staff of museums (e.g., archaeologists, museologists) and archaeomusicologists. The scientists who have found a Greek AMI (even if it is not in one piece) or even a visual representation of it (for example, on a vessel) will be able – most probably by assuming some geometrical features and materials – to hear how it sounds. They will be able to experiment further with all the parameters side by side with the relevant generated musical scales. The second category is comprised of museum visitors, musicians, or even students. The museum visitors will be able to interact via a touch screen interface (tablet) or a midi controller with the digitally simulated instrument and hear the result in real-time. This enables its use by musicians who want to experiment with the sounds of AMI. The application will also help students familiarize themselves with a variety of instruments that generate different musical scales than modern instruments.

4. Conclusion

In this work, an interactive digital tool of simulated wind and string AMIs is illustrated. This application will not only be a useful tool for scientists (anthropologists, archaeologists, and archaeomusicologists) to study the instrument's sound without the need of building pricey replicas but also for non-specialists such as the museum visitors' where such an application will enrich their experience. The user is able to alter the geometrical features of the instrument and hear the generated sound without the need of building replicas which is a time consuming and pricy procedure. We highlight the simulated techniques for four classes of wind instruments (*Aulos*, *Plagiaulos*, *Syrinx*, and *Salpinx*) using the DSP (DWGs) method and five classes of string instruments (*Phorminx*, *Chelys*, *Barbitos*, *Kithara*, and *Trigonon*) using a hybrid method based on DSP (DWGs) and FEM (solving in the Time Domain). The application allows the real-time interaction with the selected class of the digital instrument, the alteration of its parameters (i.e., geometrical features), and its 3D visual representation.

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ABSTRACT

A significant number of Ancient Musical Instruments (AMIs) are exhibited in archaeological museums all over the world. Organized sound (music and songs) was the prominent factor in the process of both formulating and addressing intellectual activity and artistic creation. Thus, the way AMIs sound is a key element of study for many scientific fields such as anthropology, archaeology, and archaeomusicology. Most of the time, the excavated instruments are not in good condition and rather fragile to move around (in order to perform studio recordings or exhibit them). Building replicas was the only way to study their performance. Unfortunately, replicas are not trivial to build and, once built, not modifiable. On the other hand, digitally simulated instruments are easier to build and modify (e.g., in terms of geometry, material, etc.), which is a rather important feature in order to study them. Moreover, the

audio stimulus and the digital interaction with an AMI through a Graphical User Interface would give more engagement and knowledge to the museum's visitor. In this work, we show the simulation methods of wind (classes: *Aulos*, *Plagiaulos*, *Syrinx*, and *Salpinx*) and string (classes: *Phorminx*, *Chelys*, *Barbitos*, *Kithara*, and *Trigonon*) Greek AMIs and the relevant built-applications useful to scientists and broader audience. We here propose a user-friendly, adaptable, and expandable digital tool which reproduces the sound of the above classes of AMIs and will: a) allow the museum scientists to create specific Auditory Virtual Musical Instruments and b) enrich the experience of a museum visitor (either in situ or on line) through a digital sound reconstruction and a 3D visual representation of AMIs, allowing real-time interaction and even music creation.

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