VIRTUAL RECONSTRUCTION OF AN ANCIENT GREEK PAN FLUTE

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ABSTRACT

This paper presents ongoing work aimed at realizing an interactive museum installation that aids museum visitors learn about a musical instrument that is part of the exhibit: an exceptionally well preserved ancient pan flute, most probably of greek origins. The paper first discusses the approach to non-invasive analysis on the instrument, which was based on 3D scanning using computerized tomography (CT scan), and provided the starting point to inspect the geometry and some aspects of the construction of the instrument. A tentative reconstruction of the instrument tuning is then presented, which is based on the previous analysis and on elements of theory of ancient Greek music. Finally, the paper presents the design approach and the first results regarding the interactive museum installation that recreates the virtual flute and allows intuitive access to several related research facets.

1. INTRODUCTION

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 the data transfer from the analogue to the digital domain. 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 [1].

In recent projects [2–4], some of the present authors have proposed to transpose these categories to the field of physical artifacts and musical instruments. In this context, passive preservation is meant to preserve the original instruments from external agents without altering the components, while active preservation involves a new design of the instruments using new components or a virtual simulation of the instruments. Specifically, the approach adopted here amounts to developing virtual counterparts in the digital domain, which retain as much as possible the characteristics of the original instruments.

Providing new means of interaction with instruments that are otherwise not accessible means also proving new means to access them on a wide scale, particularly in museum exhibits, where presenting artifacts to the general public is a complex task, because of their multi-faced nature. Interactive museum installations can increase the engagement and participation of visitors [5], and enforce new forms of learning where visitors observe and perceive artifacts by means of multiple senses and control them through movements [6], a more natural form of learning than one based on symbols, which are not accessible to perception. Ultimately, applying new technologies to interactive museum installations can create stronger consensus and interest for the preservation of cultural heritage [7].

In addition to permanent installations, museum exhibits can also benefit from mobile applications that exploit unprecedented multimedia and multisensory capabilities offered by smartphones and tablets, which are endowed with a wide range of sensors and input devices, as well as non-negligible computing power (multi-core CPUs, augmented with specialized accelerators for 3D graphics and signal processing operations). Consequently mobile devices are finding significant applications in the virtual reconstruction of environments [8] and physical objects [9], allowing the development of *skeuomorphic* user interfaces, i.e. interfaces that leverage on the appearance and behavior of physical artifacts. In this context, apps for musical cultural heritage are a particularly interesting domain.

This paper presents current results of an ongoing research project, which combines a team of researchers in such field as archaelogy, 3D scanning and modeling, and sound and music computing, around a unique artistic artifact: an exceptionally well preserved ancient pan flute, most probably of greek origins, recovered in Egypt in the 1930's and currently exhibited in the Museum of Archaeological Sciences and Art at the University of Padova. Before being included in the permanent exhibit, the flute underwent a major restoration programme for consolidation and (passive) preservation, as shown in Fig 1. 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 a previous publication [3].

The final goal of the project is to develop an interactive museum installation that virtually re-creates the instrument, and communicates different aspects related to

Figure 1. The restored pan flute (frontal and posterior views).

history, iconography, acoustics, musicology, etc., as well as the research carried out during the project. 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. 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 remainder of the paper is organized as follows. Section 2 presents the results of a campaign of non-invasive measurements performed on the flute by means of CT scanning. These measures are the starting point for the analysis of the tuning of the flute, which is discussed in Section 3. Finally, Section 4 presents the interactive applications that are being developed on the basis of these results: specifically an interactive museum installation is discussed in Section 4.1, while a mobile application is presented in Section 4.2.

2. MEASUREMENTS

It is known that the internal lengths of the pipes are reduced by carefully increasing the thickness of the closed ends through the addition of wax or propolis, in order to fine-tune fundamental frequencies [10]. Despite the restoration of the ancient pan flute, some pipes are still partially obstructed, therefore the interior of these pipes is not completely visible and not directly inspectable. In a previous work [3] a preliminary estimation of pipe lengths was obtained from external measures taken on a laser-scanned 3D model. In order to refine these measurements, computerized tomography (CT) scan was used here. Specifically, in order to determine fundamental frequencies of the pipes, two measures were estimated: internal length and internal diameter.

The three dimensional image of the interior of the instrument is obtained with a GE LightSpeed VCT 64 Slice CT scan. The scanning was then read with the open-source software Horos, a medical image viewer which also provides tools to extract reliable measures from the CT scan.

In order to browse inside the three-dimensional image, and to perform precise measures, the operators alternated two different views: a 3D MultiPlanar Reconstruction (MPR) and a 2D orthogonal MPR. Figures 2a, 2b, and 2c show the latter view and the three orthogonal planes, defined as axial, coronal and sagittal, respectively.

Since some parts are damaged or corrupted, a total of eighteen measurements for every pipe were collected, with the goal of obtaining more robust estimates.

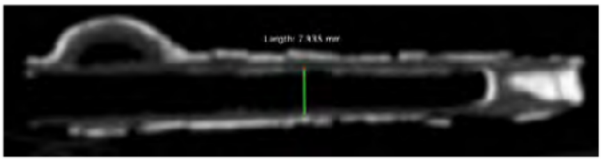
With regard to pipe lengths, six measures were extracted from axial and coronal planes. Pipe openings are not straight, they are slightly u-shaped at one side in order to provide an embouchure to the player (the opening shapes can be observed in Fig. 1, posterior view): therefore, the difference between the maximum and the minimum point of the opening was measured on both planes. Moreover, the internal shapes of the closed pipe ends are also not straight: therefore, for each plane, the maximum and minimum internal lengths were measured (Fig. 2b shows an example of measuring the maximum length of a pipe in the coronal plane).

With regard to pipe diameters, twelve measures were collected. One measure was taken in the axial plane and a second one in the coronal plane, whereas two measures were taken in the sagittal plane (one for each axis of the pipe, see Fig. 2c), because pipe sections are oval-shaped rather than circular. These four measures were repeated at three different levels: near the opening of the pipe, at the mid point and near the closed end (Fig. 2a shows a diameter measure at the mid point in the axial plane).

The measurement process highlighted several issues that required some subjective interpretations by the operators. The longest pipe, for example, is broken and curved, thus a specific tool of 3D Curved-MPR was used that, given a set of reference points on the curve, virtually straighten the pipe, providing a more usable view for the correct measurement. In other cases, the presence of obstructing materials impaired a correct evaluation of the internal surface of the pipe. This is the main reason why the authors chose to take redundant measurements. Furthermore, for the shortest pipes in was not possible to measure directly the position of the openings because these pipes are more heavily damaged. Consequently, opening positions were estimated from the neighboring pipes. The error that mostly impact the measures was the CT scan resolution: every voxel (volumetric pixel) is isometric and it measures $0,625$ mm. All these difficulties affected the accuracy of the measures, however using redundant measurements provided a range for a plausible estimation of lengths and diameters.

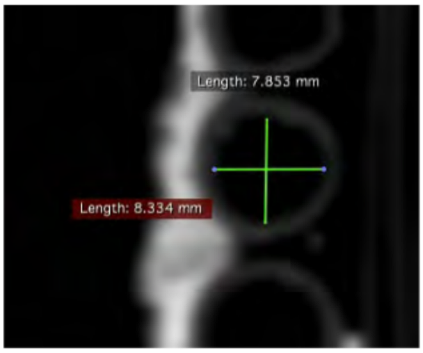
3. TUNING

The measurements of the internal length and diameter of the pipes were used to estimate their fundamental frequencies, under the assumption of ideal open-closed cylindrical



(a)

(b)



(c)

Figure 2. Views from the CT scan; (a) example of diameter measurement on the axial plane; (b) example of length measurement on the coronal plane; (c) example of diameter measurement on the sagittal plane.

pipes:

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

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, which is proportional to the internal pipe diameter d_{int} [11]. As the measurements are affected by the errors reported in the previous section, for each pipe we considered the minimum and maximum values of internal length and diameter.

Then, in order to take into account the effects of error propagation, an interval of values was calculated for each pipe as an estimate of the fundamental frequency: in particular, f_{min} was calculated from Eq. (1) using the maximum values of length and diameter, whereas f_{max} was calculated from corresponding the minimum values (see Table 1).

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.

It is interesting to verify whether these frequency ranges are compatible with predictions derived from music theory. According to theorists [12], the ancient Greek music system was based on the *tetrachord*, i.e a group of four notes (often associated to the four strings of the lyre or the kithara) where the ratio between the pitches of the fourth note and the first note is equal to $4 : 3$, namely a perfect fourth.

Figure 3 shows the pitch ratios calculated as $f(n+3)/f(n)$ for $n = 1, 2, ..., 11$, where $f(n)$ is the fundamental frequency of the n^{th} pipe. Due to error propagation, for each pair of pipes a range of values (reported with the vertical lines) was obtained. Comparing the ranges with the horizontal line representing the $4 : 3$ ratio (dot-dashed line), it is possible to see that all the intervals are compatible with the tetrachord definition.

It is known that the tetrachord is subdivided into three pitch intervals that can have various configurations. In particular, three *genera* can be distinguished: diatonic, chromatic, and enharmonic. As an example, the diatonic tetrachord is characterized by intervals that are less than or equal to half the total interval of the tetrachord. Usually, this tetrachord begins with one small interval followed by two larger intervals, corresponding approximately to a tone $(9 : 8)$.

Figure 4 shows the pitch ratios between adjacent pipes, i.e $f(n+1)/f(n)$: it is possible to recognize some intervals that are compatible with a tone $(9 : 8)$ and other smaller intervals compatible with what some theorists call *diesis*, corresponding to the ratio $256 : 234$. Two tetrachords can be joined following two different schemes, called *synaphē* (conjunction), when the top note of the lower tetrachord corresponds to the bottom note of the higher one, and *diazeuxis* disjunction, when there is an interval of a tone between the tetrachords. Observing the sequence of intervals of Figure 4, some joint tetrachords can be recognized: e.g., the pitch of the first eight pipes are compatible with two disjoint tetrachords, as represented in Figure 5.

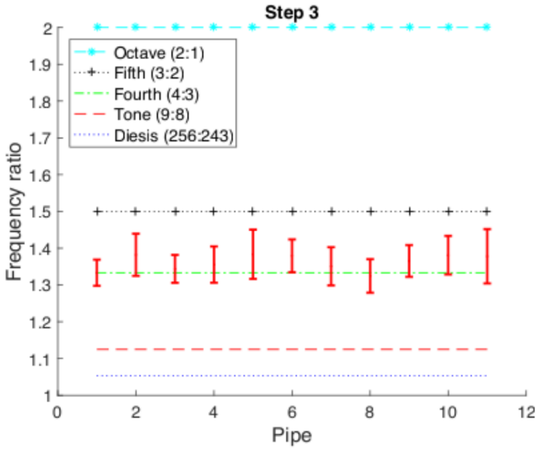


Figure 3. Pitch ratios calculated as $f(n+3)/f(n)$, where $f(n)$ is the fundamental frequency of the n^{th} pipe. The horizontal lines correspond to the basic theoretic intervals.

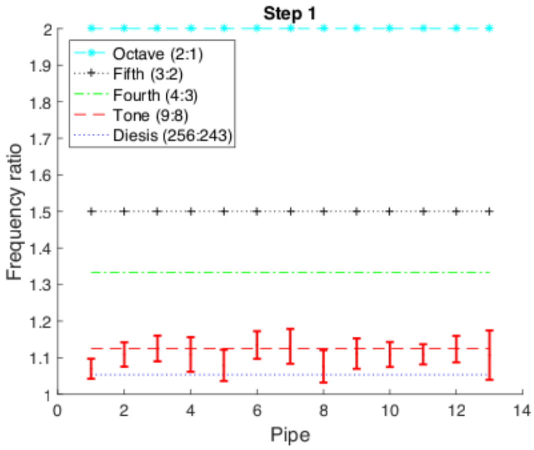


Figure 4. Pitch ratios calculated as $f(n+1)/f(n)$, where $f(n)$ is the fundamental frequency of the n^{th} pipe. The horizontal lines correspond to the basic theoretic intervals.

4. VIRTUAL RECONSTRUCTIONS

4.1 Museum installation

An interactive museum installation is being developed, and will be included in the permanent exhibit of the Museum of Archaeological Sciences and Art at the University of Padova. The installation will allow visitors to have a direct multimodal experience of the flute sound, and to access easily and intuitively to all the related information [5–7].

The installation is physically composed of two parts connected together into a single structure (see Fig. 6). These parts are designed to facilitate two different interactions: the first one (left side) is concerned with the sound, while the second one (right side) provides visual information about the musical instrument. In particular, the first part is designed to symbolically represent the 14 pipes of the flute through 14 cuts of different lengths made on the top of the furniture. The visitor can “play” the installation by blowing into the holes at the bottom of the cuts, and listening to the resulting sound from the corresponding pipe, additionally visualizing the interaction through the lighting of LED stripes placed inside the cuts.

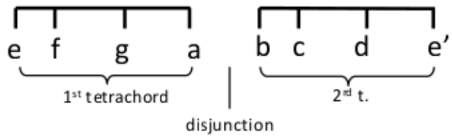


Figure 5. Schema of two disjoint tetrachords, compatible with the pitch of pipes 1-8. The letters used to represent the notes does not correspond to modern pitches.

Figure 6. The first realization of the multimedia installation.

In order to detect the air flow generated by the user, every hole is equipped with a printed circuit board (PCB) that includes a small condenser microphone and an amplification circuit, forming an array of 14 microphones [13, 14]. All the sensors are connected to an Arduino board, that estimates the amplitude envelope and the energy of the flow signal with appropriate processing, and traslates these features into MIDI messages. These in turn are sent as input to an audio interface that controls a sampler of the pan flute through Ableton Live.

The second part consists of a touch display that allows visitors to read some informations expressed through texts, photos, videos, 3D images, and illustrations that tell about different aspects of the pan flute.

The design of the installation required to take into account several elements, including the peculiarities of the architectural context of the “Liviano” Building (designed by Giò Ponti in 1932), where the exhibit is hosted. For this reason the shape and the color of the installation were chosen to be in style with the modernist architecture of the museum. Other elements driving the design were the robustness and durability of the installation, as well as the user experience.

The interaction was designed to make information as intuitively accessible as possible. Specifically, the navigation bar is composed of five different sections: *Myth, Flute, History, 3D, Sound*, all of which are represented by a hand drawing sketch and a brief description.

All the sections are characterized by a navigation bar at the bottom of the page that enables the fruition of the contents. The *Myth* and *Flute* sections contain simple textual information and images. In the *History* section, the navigation bar represents a timeline divided by key points for exploring the main iconographic sources, that will be contextualized by a map, a text and an image. The *3D* section provides two tools to interactively explore (i) a texturized 3D model of the flute (obtained from a high resolution laser scan) and (ii) the CT scan discussed earlier. The latter tool uses the navigation bar to explore points of interest in the three dimensional image.

The last section is relative to the *Sound* of the pan flute. Here the user can listen to a note relative to the pipe by touching one of 14 stylized segments. This section is strictly connected with the first part of the installation: there is only one speaker available, thus the two parts work with a mutual exclusion mechanism.

4.2 Mobile application

In addition to the installation, an Android app is being developed to access a subset of the information available in the museum, and, chiefly, a second virtual reconstruction of the pan flute. The virtual musical instrument can be played by moving the mobile device below the mouth, like an actual pan flute, and blowing at the device itself.

The reconstruction is less accurate than one that uses custom hardware. However, an app for commodity mobile devices has the advantage of targeting a much wider public, as it can be freely installed by anyone on her/his smartphone. Moreover, the app virtually takes the flute out of the museum: through the app, anyone can interact with the flute while at home and anywhere. As a consequence, the app is a definitely effective communication vessel for the activities in the project, and it fosters cultural dissemination via informal learning. Furthermore, to the best of our knowledge our app is the first virtual reconstruction of a hole-less wind instrument on commodity mobile devices that aims at a natural interaction with the instrument itself. This is in contrast with currently available simulators: the easy choice of selecting the note to play by touching the screen is reasonable for ocarinas [15], but it is unnatural if adopted – as it is nowadays – for instruments without holes such as harmonicas [16] or pan flutes.

While the virtual flute is being played, the mobile device displays a full-screen picture of the instrument and is held below the mouth of the user: the app infers the note to be played by tracking the movements of the mobile device, hence determining which virtual pipe is displayed right below the mouth. The note is played when the user blows. Blow detection is quite plain: the position of the microphones vary from device to device and hinders a reliable detection of blow intensity, hence we opted for a simple threshold detector. On the contrary, motion tracking is nontrivial and combines information from several device sensors: (a) the orientation of the device in space is detected via the accelerometer and gyroscope; (b) fast (hence, wide) movements of the device are measured via the accelerometer; (c) slow (hence, small) movements of the device are estimated by tracking the user's position via the front camera of the device.

Data from the accelerometer are processed with a Kalman filter, which improves the position estimate; misalignments or rotations of the device with respect to the direction of motion are also compensated. However, when the movements are small and acceleration is low, noise in accelerometer data and error in the orientation estimate cause drift, and a different approach is necessary.

As soon as the measured acceleration falls below a predefined threshold, the app switches to a camera-based motion estimation algorithm. While the flute is being played, the front camera frames part of the user's chin, cheek, neck, and torso (an example is shown in Figure 7). The resulting image is feature-rich enough to track the relative movement of the user with respect to the device. The reasonable assumption is made that the image does not contain independently moving objects, hence image alignment techniques can be adopted [17]. It must be noted that switching to the camera-based estimation strategy has the side benefit of resetting the position error accumulated while integrating accelerometer data. It must also be remarked that the camera cannot replace other kinds of sensors, such as the accelerometer and gyroscope, during fast motion, because in this scenario images are too blurry to be useful.

5. CONCLUSIONS

The main foreseen developments in the short term concern the tuning analysis and the virtual realizations. Regarding the first point, more reliable estimates may be obtained by exploiting more constraints about possible tunings based on elements of music theory of ancient Greek music. Regarding the second point, a thorough validation of the usability of the virtual realizations will be conducted with experimental subjects.

In the mid term the work presented here is expected to produce several developments. One is sound synthesis of the pan flute by means of physical models instead of sampling (as in the current realization), in order to increase the interactivity of the instrument. This is also an interesting research topic *per se*, since to our knowledge only one previous study on sound synthesis of the pan flute is available in the literature [18]. A very high resolution 3D model can also be exploited for computationally intensive acoustic simulations (e.g., based on finite differences or finite elements), which in turn could aid sound synthesis [19].

As far as virtual instrument reconstructions are concerned, an intesting development would be using a 3D print of the flute model (possibily "digitally restored" before printing), which can be sensorized and used as a tangible interface that recreates the physicality of the original instrument. This scenario is in line with current research on 3D printing of musical instruments [20]. However it raises various pratical concerns regarding possible uses in a museum exhibit, particularly about durability and hygienic issues.

Being the pan flute a primeval instrument which is widespread in different cultures worldwide, the impact of this research goes beyond this particular exemplary. We believe that the proposed "active preservation" approach can be applied to other ancient musical instruments.

Acknowledgments

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(a) (b) (c)

Figure 7. Mobile application: tracking small movements of the mobile device via the built-in front camera. (a): reference frame, with a yellow rectangle indicating the central portion of the frame whose motion is actually tracked. (b): a later frame, where the user roughly appears to have moved to the right (actually, it is the mobile device that is moving while the user plays the virtual flute, and the motion is not a pure translation). (c): the algorithm computes the motion, thus allowing to project the central portion of (a) onto (b) and, ultimately, to determine which virtual pipe is below the mouth of the user.

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