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ENTROTUNER: A Computational Method Adopting the Musician's Interaction With the Instrument to Estimate Its Tuning

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ABSTRACT Archeomusicologists commonly use methods based on the physical properties and the relative tuning system of a musical instrument in order to estimate its tones. However, because the musician often alters the tones' frequency, for example, while playing in wind instruments by means of embouchure or by stressing the string in string instruments, the current methods that neglect the musician's interaction with the instrument cannot provide solid results. In this work, we introduce ENTROTUNER, a computational method, based on mathematical optimization, to more accurately estimate the generated tones by considering: the instrument as a sound production mechanism, the relevant musical scale(s), and the musician's interaction with the instrument. We simulate this interaction as a system that, by following tuning rules, aims to maximize the partials' overlap (harmonicity), coded as entropy's minimization of the aggregated tones' spectrum. Last, we put ENTROTUNER into practice for the ancient Greek wind instrument Aulos. The results reveal that, compared with the traditional methods, ENTROTUNER highlights increased harmonicity (entropy decreased by 0.341bits), eleven additional consonant intervals, as well as 47.8% more tuning quality for the musical instrument.

INDEX TERMS Archaeomusicology, Aulos, computational musicology, entropy tuning, harmonicity, musician interaction, musical scale, optimizer, wind musical instrument.

I. INTRODUCTION

Archaeomusicological research primarily focuses on the findings of excavated ancient musical instruments and on relevant evidence, both iconographic and textual. On that grounds, scholars conclude regarding the ancient musical sound, which, according to modern anthropological studies, have played an important-functional role at certain activities of the members of ancient communities (i.e., theatre plays, ceremonies, dinner-parties, public gatherings, warfare, and worship activities, etc.) [1]. However, missing parts of excavated musical instruments and lack of concrete evidence on the ancient playing techniques (i.e., the players' interaction with them) lead us to ambiguities regarding their function and relation to specific tuning systems and practices [2]. An ancient musical instrument is not an apparatus detached from the cultural practices of that era but rather an item whose study can reveal unknown aspects of prior civilizations. Archaeomusicologists mainly focus on addressing two complementary tasks: a. to suggest the musical scale(s) that the ancient player was rendering based on a given tuning system(s) and b. to reveal and verify certain tuning systems of

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the past, on the grounds of the valid tones and scales derived from the available findings.

A musical instrument that can be tuned (i.e., string or wind instrument) can produce various tones whose fundamental frequencies are even unrelated ones to the tuning system. The study of this type of musical instrument as a physical object that generates sound can provide useful information regarding its acoustic properties but not directly for the tones that correspond to a relevant tuning system. A representative example is the category of fretless string instruments (e.g., the violin [3]). A musicological study aiming for more solid results regarding a tuning system should take into account both: i. the study of the musical instrument as a physical object and ii. the tuning system that was built to reproduce. However, in contrast with more recent and well-known tuning systems (e.g., just intonation, 12-tone equal temperament), there is uncertainty regarding the ancient music's tuning system as our knowledge is limited [4].

An excavated musical instrument's construction details, such as its material and geometrical features, correlated with its specific geographical origin and chronological period, provide information that, along with other relevant findings (e.g., texts and drawings), lead to assumptions regarding the era's tuning system [5]. The study of the instrument, from an acoustical point of view, would reveal even more details [6]. This is not a trivial exercise, as in most cases, significant parts of a musical instrument are missing (e.g., the cane reed of Aulos [7] and the intestinal strings of string instruments [8]).

Even in the hypothetical scenario that a musical instrument was found intact and with no missing parts, the musician's interaction with it cannot be accurately described, especially in regards to tuning [2]. The musician can adjust the tuning and intonation either by stressing the strings of a string instrument [9] or by using certain blowing and lip abutment techniques in woodwind instruments [10]. Thus, besides the two factors i. and ii. discussed above, that provide useful information to draw conclusions about the generated sound of the musical instrument, we have to take into account an additional significant factor: iii. the musician's interaction with the instrument. Numerous works consider factor iii. to derive musical conclusions for modern instruments [11], [12]. However, so far, there is not a study combining all three factors, specifically for an ancient instrument. The study of ancient wind instruments revealed a consistency of the finger hole positions' design [2] to derive a certain tuning [6]. These characteristics indicate that the study of the musical instrument alone is inadequate and highlight the necessity to adopt a more holistic approach. We here introduce ENTROTUNER, a computational method that considers the three fundamental elements of such a system, i.e. the musical instrument, the player's input and the relevant tuning system, to optimally tune the set of generated fundamentals of a musical instrument.

The musician has two concerns regarding tone production. The first one is, among the variety of frequencies, to produce those that belong to a set determined by a specific tuning system. In string instruments, this is primarily achieved by appropriately stressing the strings. A special case is the string instruments with a neck (e.g., violin, guitar) where the players place their fingers exactly in the correct place (either indicated by frets or not) to achieve good intonation. In wind instruments, we achieve good intonation and precise tuning by using probes (e.g., valves or wax) that change the effective length of the pipe, by closing/opening the fingerholes, and by means of embouchure. The latter was a common technique in the community of double-reed wind instrument (e.g., Aulos) players [6], [13]. The musician, during the performance, taking into account the aural feedback, adjusts the intonation by changing lip position and pressure on the reed [10]. The second concern is to produce the best possible sound quality. Although, recent evidence suggests that it is the cultural experience that shapes preference in sound [14], the vast majority of the musical cultures throughout history have formed scales based on intervals with the greatest overall spectral similarity to a harmonic series [15], [16]. Our work reflects to the cultures that show a clear tendency towards the optimization of consonance, for example the ancient Greek one [17], [18] which the Aulos corresponds to. Humans who are part of the aforementioned cultural groups consider a combination of sounds as pleasant, harmonic, or in tune when they perceive correlated spectra [19], [20]. Every tone consists of frequency partials, which include the fundamental and higher frequencies (overtones). The more common partials a group of tones shares, the more harmonic the result sounds in a musical piece [21].

Usually, the tuning system and the sound production mechanism of music instruments impose inharmonicities. In musical instruments, especially in the ones carrying strings, the overtone frequencies are not perfect integer multiples of the fundamental frequency but slightly deviate, a phenomenon known as inharmonicity [22]. As a result, when a musical instrument is tuned by precisely tuning the fundamental frequencies alone, according to a tuning system, it might sound out of tune because the produced partials might not coincide. For example, pianos due to their wire-strings and large frequency range are significantly affected by inharmonicities. In order to compensate this problem, professional aural tuners purposely tune some tones (especially very high and low) in frequencies that deviate from the theoretically correct ones [23].

While tuning a piano is usually done by a professional tuner, for many musical instruments tuning lies on the performer (e.g., wind instruments and string instruments with tuning pegs). The electronic tuning devices for pianos, even in our days, lack efficiency mainly due to the instruments' unique inharmonicity. Thus, in both cases, tuning depends on aural feedback. Hinrichsen [19] proposed a method to simulate aural tuning by compromising the lack of coincidence of the partials and the deviation of fundamental frequencies according to a tuning system. An entropy-based optimizer constitutes the core module of ENTROTUNER's tuning approach. The entropy of two spectral lines decreases

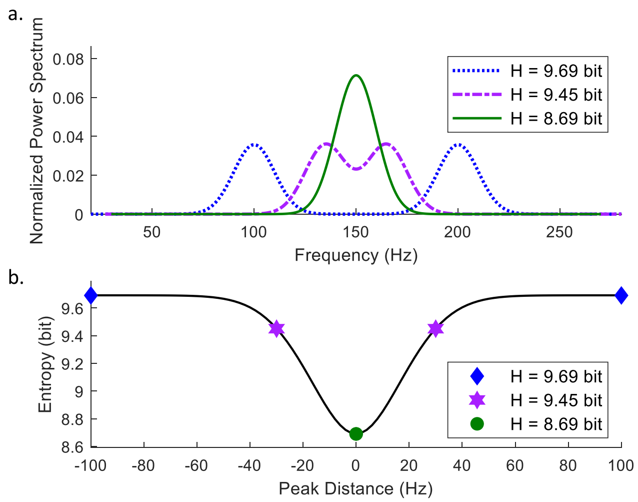

FIGURE 1. An example illustrating the use of entropy (*H*) as an indicator of overlapping spectral peaks. For not overlapping peaks (a. blue, dotted line) the entropy is maximized (b. blue diamond) $H = 9.69$ bit and independent of their distance In an overlap (a. purple, dash-dot line) the entropy's value is lower (b. purple star) $H = 9.45$ bit. When there is maximum overlap (a. green solid line) the entropy's value is minimized (b. green dot) $H = 8.69$ bit.

as they overlap (Fig. 1). We obtain the best compromise of the criteria above, by minimizing the entropy of the intensity spectrum. ENTROTUNER is applicable in every musical instrument that the player can adjust the intonation while playing. In this work, in order to validate ENTROTUNER, we choose as a musical instrument the ancient Greek Aulos, and more specifically, the Aulos of Louvre, and we compare our results of the estimated tuning with existing studies of the same instrument [6], [24].

A musician is tuning a wind instrument through aural feedback during the performance, similarly as a professional tuner is tuning a piano. ENTROTUNER calculates Aulos's tones by taking into account the player's interaction with the musical instrument. We put multiple optimization techniques in practice and illustrate their efficiency. Our method provides a more in-depth study of Aulos by considering not only the tuning system and the physics of the musical instrument but also the musician's interaction with it.

We begin in the next section with the presentation of ENTROTUNER, where first we illustrate the link between entropy and spectrum's harmonicity, and then we project in detail the elements comprising ENTROTUNER. Next, we put the proposed method in practice in order to benchmark its performance regarding the optimal tune of the set of generated fundamentals by, for the first time, taking into account the player's input. Previous relevant studies on Aulos of Louvre are presented in Subsection III-A, followed by a detailed description of how we adopted ENTROTUNER to reflect the selected musical instrument (Subsection III-B). Finally, we show our results and their comparison with previous studies ending up with a discussion about the current work and future ones.

II. METHODOLOGY

A. ENTROPY AND HARMONICITY

Multiple musical notes, when played at the same time (forming chords) or even when played in a sequence (forming melodies), are perceived as consonant or dissonant. Humans' perception of consonance relies on the overlapping frequency components of complex tones to a single harmonic series [25]. The ratio of the fundamental frequencies defines the musical intervals. For some ratios, e.g., unison (1/1), octave (2/1), and fifth (3/2), the harmonics of the relevant tones match, and that is because their combined harmonics form a single harmonic series. Ratios that do not have the above property, such as the tritone (64/45), evoke a dissonant sound [26]. Tuned musical instruments (e.g., using 12-tone equal temperament system) form intervals that cannot be expressed by small-integer ratios, and as a consequence, the intervals deviate from the theoretical values [27]. A common example is the perfect fifth (ratio $3/2 = 1.5$). In the 12-tone equal temperament the octave is divided into twelve equal parts, the semitones ($2^{1/12}$). Seven semitones ($2^{7/12} = 1.498$) comprise a fifth, which does not precisely match the theoretical value of the perfect fifth (1.5). This mismatch enforces the partials' frequency imbalance as well. While in theory the overtones are the integer multiples of the fundamental frequency (harmonic series) in reality there are small deviations (inharmonicity). The tone quality of each instrument depends on these deviations, which determine the frequency components of the spectrum. Inharmonicity significantly impacts the sounding of a combination of musical tones. In theory, the mutual frequency partials of the tones creating consonant intervals, match. However, in the physical world, mainly due to the tuning system and/or to inharmonicity, there is a mismatch. The tuner's job is to minimize this mismatch. This practice involves slightly shifting the fundamental frequency away from its theoretical value. We perceive an interval in tune, even if the ratio of the fundamentals is out of tune, primarily because of the correlated partials' frequencies. For piano tuning, this technique is called stretching. Related techniques are being used even in monophonic musical instruments, especially when they are not performing solo. Similarly, monophonic wind instrument musicians focus on tuning during playing along with the rest of the instruments of the orchestra.

Based on Hinrichsen's work [27] we express harmonicity in terms of entropy, which enables the detection of overlapping peaks. According to Shannon [28] entropy (H) is calculated by the following formula:

$$H = -\sum_{i}^{n} P(x_i) \log_b P(x_i) \tag{1}$$

where $\{x_1, x_2, \ldots, x_n\}$ are the possible values of a variable X and $P(x_i)$ is the probability of each value. We express entropy in bits, and therefore, the logarithm base (b) equals to two. There is a conceptual link between entropy and uncertainty. The maximization of entropy occurs when the values of a sample space are equally likely. That case results in a maximization in uncertainty and randomness as well. For example, the entropy's value of a fair coin is 1 bit (i.e., $P(head) = P(tails) = 0.5$). On the contrary, the more biased the coin is, the lower the value of the entropy will be. For example, if $P(head) = 0.99$ and $P(tails) = 0.01$ the uncertainty's, and as a result, the entropy's values are low (0.08bits). Entropy increases as a system's randomness increase. In terms of audio, a noise signal's entropy is high, whereas a pure tone's is low. More ordered spectrums have lower entropy than the less ordered ones. In the simple case of two single-frequency tones, which they share the same quality and strength, the more they overlap, the more ordered their spectrum is, and hence, the entropy decreases (Fig. 1). Here we use entropy to detect overlapping partials as a signature of consonance and harmony [27].

In order to express harmonicity in terms of entropy, we formulate the power spectrum ($\mathrm{PS}(f)$) as a probability density ($\mathrm{pd}(f)$). The summation of the probabilities of each value of a sample space equals to one. In the same respect, we normalize the power spectrum in the continuous domain in terms of the total power ($\mathrm{PS}_{\mathrm{tot}} = \int_0^\infty \mathrm{PS}(f)\mathrm{d}f$)

$$\mathrm{pd}(f) = \mathrm{PS}_{\mathrm{norm}}(f) = \frac{\mathrm{PS}(f)}{\mathrm{PS}_{\mathrm{tot}}} \tag{2}$$

The probability density ($\mathrm{pd}(f)$) is consistent with the properties:

$$\begin{gathered} 0 \leq \mathrm{pd}(f) \leq 1 \quad \text{for} \quad f > 0 \\ \text{and} \\ \int_0^\infty \mathrm{pd}(f)\mathrm{d}f = 1 \end{gathered} \tag{3}$$

We define the entropy of the acoustic power spectrum as:

$$H = \int_0^\infty \mathrm{pd}(f)\log_2 \mathrm{pd}(f)\mathrm{d}f \tag{4}$$

The normalized power spectrum ($\mathrm{pd}(f)$) expresses the relative amplitude of each frequency by taking into account the proximity of spectral lines in the acoustic power spectrum and a varying weighting factor of frequencies according to their intensity.

B. ENTROTUNER'S METHOD

The output of ENTROTUNER is the set of fundamental frequencies a musician should reproduce while playing a specific musical instrument. Fed with an initial set of fundamental frequencies ENTROTUNER is based on an optimization technique to conclude to a new set, which leads to a more harmonic sound (minimized entropy of the aggregate spectrum) and more accurate tuning of the fundamental frequencies (fulfilled specific musicological criteria regarding the tuning system). The tuning system provides the initial set of fundamental frequencies. In case it is not known (for example, for ancient musical instruments), the set of fundamental frequencies can be approximated via physical simulations of the relevant instruments or via assumptions based on literature.

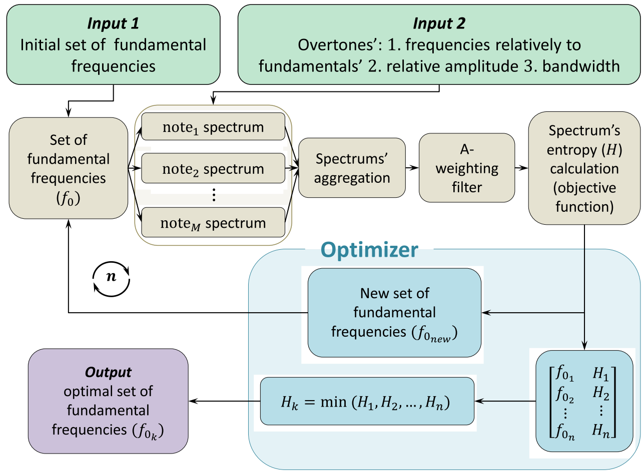

FIGURE 2. ENTROTUNER's block diagram showing the input parameters and the looping procedure to output an optimal set of fundamentals of a musical instrument.

ENTROTUNER is operating in the frequency domain. In order for it to generate the spectrum of a single note, the fundamental frequency, the frequencies of the overtones in relation to the fundamental, the relative amplitude and the bandwidth of every partial need to be introduced (see Input 1 and 2 in Fig. 2). When we have access to an instrument that is in good condition, it is a simple procedure to conclude regarding its timbre (i.e., Input 2, Fig. 2). If this is not the case, a representative musical instrument from the same family can be studied instead, or physical models (such as Finite Elements Method models) can be illuminating.

One of the musicians' main concern is the production of pleasant and harmonic sounds. In section II-A we describe how we relate entropy as a factor of harmonicity of a spectrum (ascending harmonicity results in decreasing entropy), for Aulos of Louvre. Entropy is ENTROTUNER's objective function introduced in the mathematical optimizer (see Fig. 2). Although the player can alter the tone by playing techniques (e.g., by means of embouchure), the musical instrument is built in order to favor the production of specific tones. The new set of fundamental frequencies the optimizer is trying at every iteration (see Fig. 2) should be within limits dictated by the musical instrument. Moreover, for the ENTROTUNER to encounter the musician's second significant concern (i.e., the production of a specific tuning system) the proposed constraints should take into consideration the corresponding intervals.

In every iteration, the optimizer generates a set of fundamental frequencies that are within the predetermined limits. The pillars of ENTROTUNER include the fundamental frequencies (generated at every iteration) and instruments timbre (Input 2, Fig. 2) to generate the spectrum of each tone (second step brown box, Fig. 2). In order to capture all the possible melodic and harmonic arrangements of tones, the aggregate spectrum of the instrument (which is the summation of all the tones' spectrum) is created (third step brown box, Fig. 2). ENTROTUNER uses Gaussian pulses to simulate the bell-shaped spectrum of musical instruments, as proposed in [27]. In the next step, in order to take into consideration psychoacoustic phenomena, an A-weighting filter is applied. Next, we calculate the objective function.

The number of iterations (n, Fig. 2) needed to ensure good results depend on the number of variables and the optimization method used. After the completion of the optimization process, ENTROTUNER outputs an optimal set of fundamental frequencies, which optimally considers the musician's concerns regarding tone production (Section I).

Because the study of every musical instrument dictates a different number of variables (i.e., the fundamental frequencies) and different mathematical descriptions of the reference tuning system (i.e., type of significant intervals) the objective function will have, we cannot propose an optimal mathematical optimizer for every case. Since optimization techniques are usually time-consuming, the evaluation of a method does not only depend on the quality of the output but also on the computational time needed to reach it.

III. AULOS CASE STUDY

A. PREVIOUS WORK

In the current work, we chose to put ENTROTUNER in practice and demonstrate its results for the Aulos of Louvre. We chose to use this particular musical instrument because it has already been studied before [6], [24], and therefore we can compare the results from our proposed method with those derived from previous approaches.

Aulos, a well-studied wind instrument [5], [24], [29]–[35], is comprised of two pipes with double-reeds attached. The performer blows through the reeds in both pipes at the same time, and as a result, two tones are simultaneously generated [6]. In most cases, the excavated pipes were missing their upper end (reed) [34]. This leads to a lack of knowledge regarding the total length of the musical instrument (L), which is the excavated part (L_{exc}) and the missing reed (x). Landels was the first to propose a method to mathematically calculate the produced tones, despite the restriction of the unknown effective length, by considering the law of physics that govern wind instruments [33], [34]. An approximation of the wavelength (λ) of the fundamental generated tone from a length (L) open-close pipe [36] can be calculated by (5)

$$\lambda = \frac{L}{4} \tag{5}$$

Equation (5) stands for any closed-open pipe. Taking into account that the reed's opening is relatively small, we simulate Aulos as a closed-open pipe. Further, we assume that the first open fingerhole defines the effective length of the bore [37].

Assuming that it was tuned to a musical scale the tone of two fingerholes (whose distance from the top of the excavated part is L_1 and L_2 respectively) should give a certain concordant interval, which for ancient Greek scales was the fourth (ratio of fundamentals' frequencies of 4/3). Hence, we can calculate the effective length of the pipe and the length of the reed by the expected ratio of the corresponding wavelengths

$$\frac{x + L_1}{x + L_2} = \frac{4}{3} \tag{6}$$

Once the length of the reed re-adjusts the distance of each fingerhole, we can derive the instruments' tones.

Landels is considering only the length from the top of the instrument to the fingerholes and by using (5) calculates the set of fundamentals. Hagel, based on Benade [38], improved the physical description of the effective length by adding an end correction accounting for more physical properties (such as sound velocity and the diameter of both the bore and the fingerholes). Moreover, whereas Landels' method studies each pipe independently, Hagel [6], taking into consideration the indications that favor ancient heterophony, proposes that the tones that form the concordant intervals were not only encountered on each pipe but might have been distributed between the two pipes of the Aulos as well. This method to calculate the produced tone is applicable for each fingerhole separately.

Andreopoulou and Roginska [13], by implementing a digital physical model of the musical instrument, introduced a method taking Landels' work (who is only considering the air column inside the bore) further. This design is considered to be more comprehensive by including a set of physical parameters, such as the type of the reed, the placement and size of the fingerholes, the active length of the pipe and its inner and outer diameters. Once the fundamental frequencies are calculated, possible matches to known tetrachord tunings are investigated.

The methods mentioned above provide estimations of the Aulos tones, intervals, and tuning [6], [13], [33], [34]. Their common ground is that they all connect the physical properties of the musical instruments with well-established assumptions of the ancient Greek tuning system. By putting these methods into practice, our knowledge of the use of old musical instruments and the musical practices of the time is extended. However, a significant factor, which is the player's interaction with the musical instrument, has not been taken into account in archeomusicological studies when studying a specific instrument.

Tuning in string instruments takes place before playing by adjusting the stress of the strings. This is not the case for woodwind instruments where the musician can adjust the intonation while playing through various techniques [10]. Therefore, the study of the geometrical and physical properties of a wind instrument, along with the fingering, does not ensure concrete results for the produced tone. A wind instrument musician often tunes the generated tone at will while playing by a constant real-time aural feedback. Despite the uncertainty on results that the player's input introduces, the described approaches should not be considered redundant.

FIGURE 3. The replica of Poseidonia's Aulos physically reconstructed by Chr. Terzēs.

The musical reproduction needs forced musical instrument makers to follow certain construction patterns [2].

B. BUILDING THE MODEL

In order to build our model, before taking into consideration the player's input, we first estimate the produced frequencies taking into account the two other factors, i.e., the physics of the musical instrument and the tuning system. ENTROTUNER takes into account the theoretical values of the primary set of fundamental frequencies for each possible fingering in the case of the Aulos of Louvre as already published in [24].

The next step is to program ENTROTUNER to design the musical instrument's spectrum. Because making excavated musical instruments sound again as they use to is not a trivial task, mainly due to the fact that they are deformed and parts of them are missing, we obtain the overtones' frequencies and partials' relative amplitude and bandwidth [39], [40], through recordings. Whereas Hagel uses the theoretical values for these based on ideal models and assumptions [6], we instead use values obtained by recording single notes yielded on both pipes of a 1:1 scale replica[1] of the Poseidonia Aulos find, dated in the 5ct BCE (Fig. 3). This specific instrument is a typical representative of the classical Greek Aulos in terms of dating, geometry, and function. Therefore, its acoustic study enables us to suggest generalized indications on the sound of auloi of the classical era. For the measurements, we used an electroacoustic chain (microphone: SD Systems LCM 85 MK II with "LP" Preamp Power Supply, soundcard: apogee duet, computer: MacBook air 2019) with flat frequency response in a non-reverberant room. The recordings took place at the studio of the National and Kapodistrian University of Athens, Department of Informatics and Telecommunications, on September 30th, 2019. Chrēstos Terzēs successively produced the fundamental notes of each pipe's scale. Then, we derived the spectra of the steady-state tones.

We used the least-squares method to determine inharmonicity expressed by the deviation in cents (c) and relative amplitude (A) of each possible overtone (n) ((7) and (8)). The decimals of (8) play an important to create a spectrum with precision.

$$\begin{aligned} c[n] &= 0.0004n^5 - 0.0176n^4 \\ &\quad + 0.234n^3 - 1.324n^2 + 2.886n - 1.825 \end{aligned} \tag{7}$$

$$\begin{aligned} A[n] &= 0.003115n^6 - 0.125597n^5 \\ &\quad + 1.970063n^4 - 15.107851n^3 + 58.485978n^2 \\ &\quad - 106.589891n + 60.926148 \end{aligned} \tag{8}$$

To take into consideration all the possible melodies and chords produced by the musical instrument, we create the aggregate spectrum of all the tones, played by all the possible fingerings for both pipes of the Aulos, and calculate its entropy. The elements required to synthesize the spectrum are the fundamental frequencies (derived theoretically from the geometry of the musical instrument [6], [24], [38]), the overtones' frequencies and relative amplitude (derived from (7) and (8) formed through recordings). In musical acoustics, reed instruments of cylindrical shape, simplified models are being described as open-close pipes that, in theory, give only the odd harmonics [41]. However, measurements and recordings reveal that even harmonics are present as well in the spectrum, also noticed in certain registers of the similar cylindrical and reed driven instrument, the clarinet [42], [43]. The spectrum of the studio recorded reconstructed Poseidonia's Aulos playing E4 tone is shown in Fig. 4. In our calculations, we took into consideration only the overtones whose power was 20dB lower than the fundamentals and above. We neglect the lower amplitude ones as non-significant. The number of partials satisfying the above criterion was, on average, twelve. Thus, that was the number of partials used to synthesize the spectrums. The partials' bandwidth was also derived though measurements by applying a normal distribution of standard deviation $\sigma = 5$ cents. An example of a computed spectrum compared to the recorded one is shown in Fig. 5. It should be noted at this point, that in order to take into account the musician's tuning input, we apply an A-weighted filter on the synthesized spectrum to allow for the human aural perception [44].

To study Aulos's possible combinations of tones (generated by two pipes) we created their aggregate spectrum. The spectrum's entropy defines the level of harmonicity between all the possible combinations of sounds. An Aulos player by slightly shifting the fundamentals is aiming to a more harmonic result.

[1]This particular replica of the Poseidonia aulos was physically reconstructed by Chr. Terzēs in June 2017 at the premises of the Speech and Accessibility Laboratory of the National and Kapodistrian University of Athens, Department of Informatics and Telecommunications, on the course of the HERMES: "Towards a training music archaeology project on the reconstruction and use of ancient Hellenic Musical Instruments" project implementation. This specific reconstruction is based on detailed images, measurements, and designs of the original find provided by Reichlin-Moser, Paul J. & Barbara [2013] in Der Paestum Aulós aus der Tomba del Prete. (Illustration by Verena Pavoni, Visuelle Gestaltung: Ulrich Schuwey).

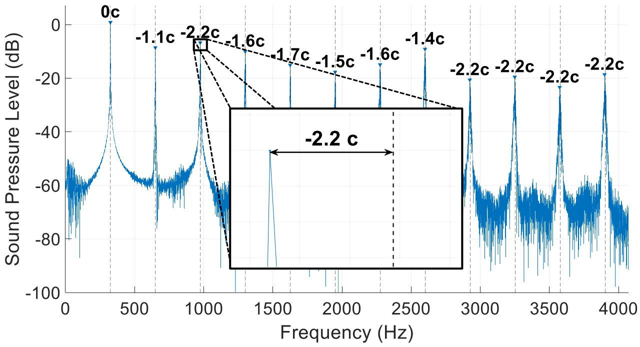

FIGURE 4. **The spectrum and inharmonicity of the recorded replica of Poseidonia's Aulos playing the fundamental tone of 325.3Hz. The deviation in cents from the expected harmonics (integer multiples of the fundamental frequency, indicated by the horizontal dotted lines in the as shown in zoomed window) of each overtone.**

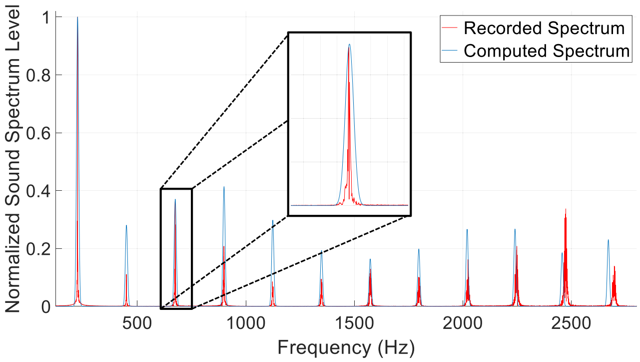

FIGURE 5. **The spectrum of a tone with a fundamental frequency of 225Hz. The red line is the recorded spectrum of Posidonia's Aulos and the blue one ENTROTUNER's computed spectrum.**

Entropy constitutes the optimizer's objective function. ENTROTUNER's task is to find the set of fundamental frequencies that minimizes the entropy of the aggregate spectrum of Aulos. Repeated patterns in construction details of the ancient musical instruments indicate that they were built to favor certain frequencies [2]. Therefore, the proposed modified set of fundamentals should not significantly variate from the initial one [24]. For that reason, we added two constraints on the variables (set of fundamentals) the optimizer tries at every iteration: a. fundamentals' deviation of $\pm$20cents (as per [6], [13]) and b. fundamentals' significant intervals deviation of ± 5 cents for at least half of them. In this study we considered the most significant intervals (regarding the second constraint) to be the fourth ($a_{k1} = 4/3$), the fifth ($a_{k2} = 3/2$), the octave ($a_{k3} = 2/1$) and the unison ($a_{k4} = 1/1$). This constrain is for frequency ratios of the fundamentals which initially present a clear tendency towards the aforementioned intervals. From the initial set of fundamentals, 45 significant intervals are formed [24] (deviating by a maximum of $\pm$20cents from the perfect ratio of the relevant interval). Our optimizer accepts sets of fundamentals that form at least 23 significant intervals approaching a perfect tuning of a maximum deviation of $\pm$5cents, which is the Just Noticeable Difference [45]. Table 1 shows the first four fundamentals of each pipe of Aulos [24], four significant intervals and their bounds.

TABLE 1. **The initial set of fundamentals derived from [24] and the constrains on the variables the optimizer tries at every iteration.**

	Initials	Bounds
Fundamentals low pipe (Hz)	f_{A1}=183.5 f_{A2}=206.4 f_{A3}=218.5 f_{A4}=243.9 …	$[f_{Ax} - 2^{\frac{20}{1200}} f_{Ax}, f_{Ax} + 2^{\frac{20}{1200}} f_{Ax}]$
Fundamentals high pipe (Hz)	f_{B1}=182.5 f_{B2}=214.6 f_{B3}=244.2 f_{B4}=271.2 …	$[f_{By} - 2^{\frac{20}{1200}} f_{By}, f_{By} + 2^{\frac{20}{1200}} f_{By}]$
Significant intervals	$\frac{f_{A4}}{f_{A1}} \approx \alpha_{k1}$ $\frac{f_{B1}}{f_{A8}} \approx \frac{1}{\alpha_{k3}}$ $\frac{f_{B9}}{f_{A3}} \approx \alpha_{k3}$ $\frac{f_{B9}}{f_{A4}} \approx \frac{1}{\alpha_{k1}}$ …	$[\alpha_{kw} - 2^{\frac{5}{1200}} \alpha_{kw}, \alpha_{kw} + 2^{\frac{5}{1200}} \alpha_{kw}]$ or $[\frac{1}{\alpha_{kw}} - 2^{\frac{5}{1200}} \frac{1}{\alpha_{kw}}, \frac{1}{\alpha_{kw}} + 2^{\frac{5}{1200}} \frac{1}{\alpha_{kw}}]$

In order to calculate the optimal set of fundamentals, we put in practice four optimization techniques. We compared their efficiency and embed the winner to ENTROTUNER. The mathematical optimizers tested here are: a. Nelder-Mead method, b. Hinrichsen's technique modified (no quantization step), c. Hinrichsen's original method with a quantization step of 1 cent for the variables as proposed by the author [19], and d. Simulated Annealing. In order to benchmark the performance of methods, we run the relevant algorithms 100 times for 50k iterations per time. The exception is the Nelder-Mead method, which run only once, since MATLAB's function "fminsearch", implementing this method, runs identically every time. Nelder-Mead and Hinrichsen's method with no quantization achieved the best cost value (minimum value after 50k iterations = 13.3948). However, Hinrichsen's method with no quantization has approached this value (within 0.0001 error of the best cost 33%) only 6% the code run. Nelder-Mead method faster came back with the best cost value (7.2k iterations), than Hinrichsen's with no quantization (25k – 48k iterations). The method proposed by Hinrichsen (with quantization) reached its best cost (13.3958) in less than 700 iterations but has not been proved efficient compared to the overall best cost value. We found Simulated Annealing to be the least efficient as it did not manage to approach the overall best cost value (13.4974). Table 2 presents the optimizers' performance.

TABLE 2. Optimizers' performance.

	Best cost	% Best overall cost
Nelder-Mead	13.3948	100%
Hinrichsen's modified (no quantization)	13.3948	6%
Hinrichsen's original method	13.3959	0%
Simulated Annealing	13.4974	0%

TABLE 3. The calculated optimal set of fundamentals: PMBM's [24] and ENTROTUNER (FH: Fingerhole, ET: ENTROTUNER, Dev: Deviation in cents).

FH	Pipe L			Pipe H		
	Frequency (Hz)		Dev.	Frequency (Hz)		Dev.
	PMBM	ET	(c)	PMBM	ET	(c)
0 (exit)	183.5	181.4	-20	182.6	181.4	-12
1	206.4	204.0	-20	214.6	216.8	18
2	218.5	216.8	-13	244.2	243.3	-7
3	243.9	243.3	-5	271.2	270.8	-3
4	269.5	270.8	8	288.3	289.5	7
5	288.3	289.5	7	324.7	325.1	2
6	327.8	325.1	-14	362.0	361.2	-4
7	363.5	361.2	-11	400.9	405.6	20
8	–	–	–	431.8	432.9	-2
9	–	–	–	484.4	486.2	-13

TABLE 4. Calculated consonant intervals and their deviation from pure intervals in cents (Int.: Intervals, Dev: Deviation in cents).

Between Pipes L and H

Int.	Hole on H	Hole on L	Dev. (c)
1:1	0	0	0
1:1	1	2	0
1:1	2	3	0
1:1	3	4	0
1:1	4	5	0
1:1	5	6	0
1:1	6	7	0
2:1	0	7	-7
2:1	6	0	-8
2:1	7	1	-11
2:1	8	2	-3
2:1	9	3	-1
3:2	0	4	-8
3:2	1	6	-1
3:2	2	7	-18
3:2	3	0	-8
3:2	5	2	-1
3:2	6	3	-18
3:2	7	4	-3
3:2	8	5	-5
3:2	9	6	-5
4:3	0	3	10
4:3	1	5	2
4:3	2	6	4
4:3	3	7	1
4:3	2	0	10
4:3	3	1	-8
4:3	4	2	2
4:3	5	3	4
4:3	6	4	1
4:3	8	6	-2
4:3	9	7	17

Within Pipe L

Int.	Hole 1	Hole 2	Dev. (c)
2:1	0	7	-8
3:2	0	4	-8
3:2	2	6	-1
3:2	3	7	-18
4:3	0	3	10
4:3	1	4	-8
4:3	2	5	2
4:3	3	6	4
4:3	4	7	1

Within Pipe H

Int.	Hole 1	Hole 2	Dev. (c)
2:1	0	6	-7
2:1	1	8	-3
2:1	2	9	-1
3:2	0	3	-8
3:2	1	5	-1
3:2	2	6	-18
3:2	3	7	-3
3:2	4	8	-5
3:2	5	9	-5
4:3	0	2	10
4:3	1	4	2
4:3	2	5	4
4:3	3	6	1
4:3	5	8	-2
4:3	6	9	17

IV. RESULTS AND DISCUSSION

A. CASE STUDY: AULOS OF LOUVRE

Table 3 presents the optimal set of fundamentals derived by ENTROTUNER and Hagel's method [24] (referred to as Physical Model Based Method (PMBM)). The numbering of fingerholes in ascending order is from the lower end of the musical instrument to the reed. The value 0 corresponds to all fingerholes closed. The higher pipe of the Avlos of Louvre is referred as pipe H and the lower one as pipe L. The mean absolute deviation of fundamentals is 10.3cents [24]. For four out of the 18 variables (fundamentals), the optimizer has chosen values close to the maximum available deviation determined by the constraints (±18-20cents), while two valuables only slightly deviate (within ±2cents). Hagel's proposed set of fundamentals shows proximity between the relevant values of the two pipes (forming unison intervals which deviate from the pure one) whereas, ENTROTUNER set of fundamentals coincide (forming pure unison, 0 cents deviation), demonstrated in Table 4. This is a clear indication of how significance is to include the player's input in a system that calculates the generated tones of a musical instrument. That is because the player further alters the produced sound during playing, aiming for perfect tuning. From the proposed set of fundamentals, the resulted consonant intervals, as well as their deviation from pure intervals, are shown in Table 4.

In order to evaluate our results, we examine their reflection regarding the player's input, compared with those of Hagel [24]. As far as the player's first goal, i.e., the generation of tones according to a tuning system, is concerned, we examine the number of the derived significant intervals (unison, fourth, fifth and octave) and their tuning quality. With our proposed set of fundamentals we find 11 additional consonant intervals than Hagel (56 instead 45). Furthermore, we have

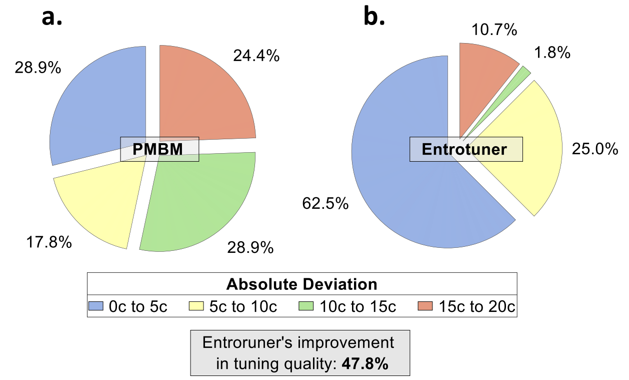

FIGURE 6. The percentage of consonant intervals (unison, octave, fifth and fourth) for Aulos of Louvre deviating within 0-5 cents (blue), 5-10 cents (yellow), 10-15 cents (green) and 15-20 cents (red) with a. PMBM's method [24] and b. ENTROTUNER.

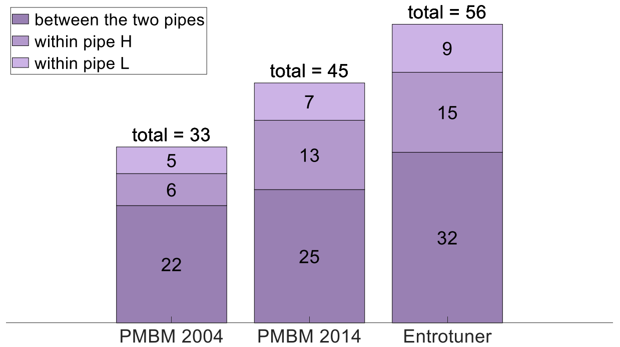

FIGURE 7. The number of calculated consonant intervals (unison, octave, fifth and fourth) for Aulos of Louvre with a maximum deviation of ±20 cents from PMBM 2004 [6], PMBM 2014 [24] and ENTROTUNER.

obtained significantly improved intervals in terms of tuning. The 62.5% of our set of intervals are within the Just Noticeable Difference (deviation of ±5cents), and 87.5% deviate by only ±10cents. Hagel's values are 28.9% and 46.7%, respectively. The average absolute deviation for our proposed values is 5.46, whereas for Hagel is 10.46, an improvement of 47.8% (Fig. 6).

According to the results of this work, the entropy of the aggregate spectrum is decreased by 0.341bits (from 13.736bits for Hagel's set of fundamentals to 13.395bits for ours). Thus, our estimated values result in a more harmonic available combination of sounds. In order for the reader to get an intuition regarding the physical meaning of the entropy values, we present two examples: A) the entropy of the aggregate spectrum of a diatonic scale tuned in just intonation is 0.025bits less than the one tuned in 12-tone equal temperament (just intonation results in a more harmonic combination of tones than that of 12-tone equal temperament [46]), B) the entropy of the spectrum of two tones forming the perfect fifth is 0.137bits less than the dissonant tritone (64/45).

Consequently, the analysis of the results reveals that our methodology addresses the musician's goal compared with the estimation of the most recent and solid examination of Aulos of Louvre.

Hagel studied Aulos of Louvre first [6] and recalculated the tones produced by the instrument according to more precise geometrical details later on [24]. The more recent one led to a higher number of consonant intervals (see Fig. 7 PMBM 2004 & 2014). ENTROTUNER sets the bar even higher further increasing the number of consonant intervals to 56 (23 more than Hagel's first approach and 11 more than his second, see Fig. 7). The increase in consonances demonstrates the validity of the approach [24].

B. VERIFICATION

Following the verification methods of previous studies (estimating the Aulos' musical scales [6]) we demonstrate that ENTROTUNER's proposed frequencies are indeed playable by an expert Aulos player. For both the measurements and the calculations of the initial set of frequencies [47] (to feed the ENTROTUNER), we used the replica of Aulos of Poseidonia (referred in section III-B) with effective reed lengths of 4.85cm and 5cm for the low and high pipe, respectively. ENTROTUNER's performance in this case is again satisfactory (increased harmonicity - entropy decreased by 0.197bits, 5 additional consonant intervals, as well as 46.2% more tuning quality).

TABLE 5. ENTROTUNER's verification: ENTROTUNER's proposed set of frequencies vs the measured ones from an expert player (FH: Fingerhole, ET: ENTROTUNER, Dev: Deviation in cents).

FH	Pipe L			Pipe H		
	Frequency (Hz)		Dev.	Frequency (Hz)		Dev.
	ET	Measured	(c)	ET	Measured	(c)
0 (exit)	204.7	204.9	2	225.6	226.0	3
1	216.7	217.0	2	240.7	240.2	-4
2	240.7	241.0	2	263.8	263.1	-5
3	263.8	263.8	0	289.2	289.1	-1
4	289.2	290.1	5	321.1	320.9	-1
5	321.1	320.2	-5	360.6	359.0	-8
6	360.6	358.9	-8	405.3	405.0	-1

An expert player (Dr. Chr. Terzēs) effortlessly played unison (verified by MATLAB spectrum analyzer of the recorded samples, available online, recorded in the studio of the National and Kapodistrian University of Athens, Department of Informatics and Telecommunications, on February 18th 2020) with the ENTROTUNER's proposed frequencies (emitted by Beyerdynamic DT990 PRO 250ohm, from a MATLAB sinewave generator, the rest of the electroacoustic chain can be found in section II-B). Table 5 demonstrates that the expert player actually performed, in all cases, ENTROTUNER's proposed frequencies, deviating by 3.4 cents in average. It should be noted here that in this frequency range any difference below 10 cents is not noticeable [48].

V. CONCLUSION

In this work, we introduce ENTROTUNER: a method that is taking into account the musician's interaction with the instrument to optimally tune the set of generated fundamentals.

It is not trivial for the archaemusicologists to find: a) skilled players and b) replicas of ancient musical instruments [1], [6], in order to carry out musicological studies and extract useful information. The proposed simulation of the player's interaction overcomes the limitations of the previous approaches. Moreover, it provides a powerful tool that gives a robust indication of the generated tones. As a case study, we used the Aulos of Louvre and compared our results with the existing literature [24]. We found a significant increase both in the tuning quality of the musical instrument (47.8%) and in the consonant intervals (11 additional). The ENTROTUNER's predicted tones and the corresponding intervals result in the re-determination of the musical scales and a more in-depth understanding of the musicological aspects of an era. Our future studies we intend to test ENTROTUNER with other musical scales, such as the 72-tone equal temperament system [49], [50]. We expect that this work will enhance the expression of harmonicity in terms of entropy to be used more widely in the computational musicology not only for studying musical instruments and musical scales but also in Music Information Retrieval (MIR) and in music-oriented machine learning applications.

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