Synthesizing Tradition: Physical Modeling and Composition with the Colombian Gaita

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Abstract. *This article focuses on the physical modeling of the Colombian gaita using waveguide synthesis techniques. Based on an acoustic analysis of the instrument, the* `gaitacol~` *object was developed in the MAX/MSP environment to simulate its sound in real time. The resulting synthesis was integrated into the composition Entre tanto y tanto, un caminar continuo, where the dialogue between the acoustic and digital versions of the gaita explores the convergence of traditional sound and technological processes. This work contributes to the field of computer music by applying physical modeling to a non-Western instrument and proposing creative frameworks for its integration into contemporary composition.*

1. Introduction

Traditional musical instruments are not only cultural artifacts but also complex acoustic systems that offer rich possibilities for scientific and artistic exploration. Among them, the *gaita colombiana* (Colombian gaita) stands out as a traditional wind instrument widely used in Caribbean Colombian music, known for its distinctive sound and cultural relevance.

This paper presents a research project that combines acoustic analysis, sound synthesis, and musical composition, focusing on the *gaita colombiana*. The study aims to investigate the physical and acoustic behavior of the instrument and apply physical modeling synthesis techniques to digitally recreate its sound. This synthesis model is then incorporated into the composition of a mixed work for electronics and acoustic instruments.

The research begins with a study of the gaita's physical properties, guided by the wave equation and principles of acoustics. Subsequently, a digital model of the gaita was implemented using the digital waveguide method in Max/MSP, resulting in the creation of a custom object named `gaitacol`. This model served as the basis for the synthesis of the instrument's sound. Finally, the musical piece *Entre tanto y tanto, un caminar continuo* was composed, integrating both the synthetic gaita and live elements into a contemporary musical context.

By integrating traditional acoustics, digital technology, and creative composition, this work contributes to the expansion of physical modeling synthesis techniques and encourages the exploration of traditional instruments in contemporary music-making.

2. Context and Construction of the Colombian Gaita

The gaita is a traditional wind instrument from Colombia's Caribbean coast, originally linked to indigenous musical practices but now used throughout the country in various contemporary musical contexts. The term "gaita" also refers to a musical rhythm used to accompany the instrument; however, in this work, it exclusively denotes the instrument itself. Although the exact origin of the gaita is unknown, some traditional players from the *Serranía de San Jacinto* region attribute it to the *Kogui* indigenous people, who inhabit the *Sierra Nevada de Santa Marta* [1].

There are two main types of gaita based on length: the *gaita larga* (long gaita) and the *gaita corta* (short gaita). The long gaita measures approximately 75 to 85 cm (excluding the head), while the short gaita is between 48 and 53 cm long [2, p. 29]. This study focuses on the long gaita, which exists in two variations known as *macho* (male) and *hembra* (female). Both have the same construction and length. The instrument consists of two main parts: the mouthpiece, called the *cabeza* (head), and the body, known as the *palo* (stick) [2, p. 36].

The body is traditionally made from a branch of *cardón*, a cactus native to northern South America, which is hollowed out by inserting a heated iron rod through its center. The external bark is then peeled to leave a tube approximately 3 to 7 millimeters thick. The length of the tube was historically tailored to the arm length of the player, ensuring ergonomic comfort [2, p. 36]. Due to the natural form of the cardón, the resulting tube is quasi-cylindrical, slightly wider at one end.

The head is crafted from a mixture of beeswax and finely ground charcoal; ideally, the beeswax is sourced from mountain bees for better moldability and temperature resistance [2, p. 40]. The melted wax-charcoal paste is shaped cylindrically and cut to create an opening for the air to pass through. A turkey feather, or more recently a cut syringe needle protector, is affixed to serve as the air slit, directing the air flow. The feather is secured with thick thread to the wax mass and assembled onto the palo. The angle and distance between the air slit and the tube edge, roughly 3 to 4 cm, are adjusted to optimize sound production [2].

The gaita produces sound by air being blown into the mouthpiece and split by the edge of the palo, resembling the sound production in flutes such as the recorder or the quena. However, unlike free reed instruments, the gaita's air stream is channeled through the feather slit held by the wax head, simplifying the embouchure for the player.

Finger holes on the gaita are made with a heated 3/8-inch rod, spaced according to the player's finger size, usually four or five fingers from the tube's bottom [2, p. 37]. The female gaita has five holes, while the male version has two, corresponding to the two lowest holes on the female instrument (see Figure 1).

According to [2], modern gaitas may be constructed from alternative materials such as aluminum, PVC, or carved wood, primarily due to the scarcity of cardón near villages, compounded by safety concerns in regions like the Serranía de San Jacinto. These alternative materials affect the instrument's timbre because the resonance characteristics vary with the material's density and surface texture. Smooth inner walls, as in aluminum or PVC, produce a cleaner sound, whereas the natural cardón surface contains fibrous material that adds a "dirty" or noisier quality to the tone [2, p. 40]. Additionally, the thickness of the tube's edge where it joins the head influences the timbre: a thinner edge results in a cleaner, brighter sound resembling a quena, while a thicker edge produces a "dirtier" sound with more noise content. These descriptors of "clean" and "dirty" relate to the amount of noise or irregularities in the sound signal [2].

Figure 1: A pair of detachable gaitas, constructed with an aluminum body covered in a wooden veneer.The gaita heads are assembled with the tube of the female gaita (five holes) or the male gaita (two holes). This facilitates their portability.

3. Acoustics of the Gaita

The colombian gaita produces its characteristic sound through the interaction of airflow and acoustic resonances inside a cylindrical air column. From a physical standpoint, the sound generation can be described by the one-dimensional acoustic wave equation:

$$\frac{\partial^2 p(x,t)}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 p(x,t)}{\partial t^2}, \qquad (1)$$

where $p(x,t)$ represents the acoustic pressure variation inside the bore at position x and time t, and c is the speed of sound in air [3].

It is possible to consider the wave equation in the physical context of an open tube, as is the case for the Colombian gaita. Let us suppose a tube of length L, open at both ends. Due to the boundary conditions on the tube, there should be no pressure variation at its ends; that is, the pressure inside the tube p_t at $x = 0$ and at $x = L$ must be equal to the atmospheric pressure p_0, having the condition $p_t(x = 0) = p_t(x = L) = p_0$. Since the wave equation (1) refers to the pressure variation $p(x,t) = p_t(x,t) - p_0$, the boundary condition at the tube ends must be

$$p(0,t) = p(L,t) = 0. \qquad (2)$$

Figure 2 illustrates a tube of length L with the boundary conditions for the pressure variation at $x = 0$ and $x = L$.

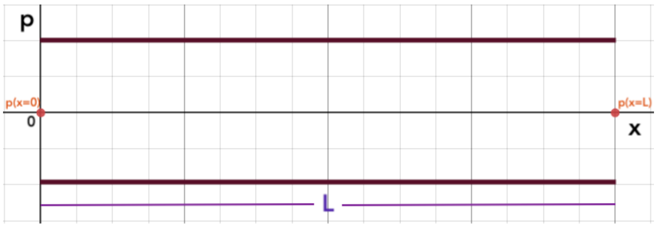

Figure 2: Diagram of a tube open at both ends, with the condition that the pressure variation is zero at $p(x = 0) = 0$ and $p(x = L) = 0$.

Given the boundary conditions derived from the physical characteristics of an open-open tube, the wave equation admits solutions that satisfy $p(0,t) = p(L,t) = 0$. These conditions lead to standing wave solutions composed of sinusoidal spatial modes. As each mode of vibration $p_n(x,t)$ satisfies the wave equation independently, the total solution can be expressed as the superposition of all such modes:

$$p(x,t) = \sum_{n=1}^{\infty} D_n \sin\left(\frac{n\pi}{L}x\right) \sin\left(\frac{n\pi}{L}ct\right) \qquad (3)$$

where D_n is a mode-dependent amplitude coefficient. The spatial part $\sin\left(\frac{n\pi}{L}x\right)$ ensures that the pressure variation is zero at the tube ends, as required by the boundary conditions, and the temporal part describes the oscillatory behavior of each mode with angular frequency $\omega_n = \frac{n\pi c}{L}$. The coefficients D_n determine the relative contribution of each harmonic mode to the overall pressure distribution[1].

Figure 3 illustrates the first four modes of vibration in the tube, corresponding to the pressure variation $p(x,t)$.

4. Modeling the Gaita

A waveguide is a computational model that simulates wave propagation within a physical medium, such as an air column inside a tube or a vibrating string. In its basic form,

[1]This reflects the complex harmonic spectrum typical of real instruments such as the gaita.

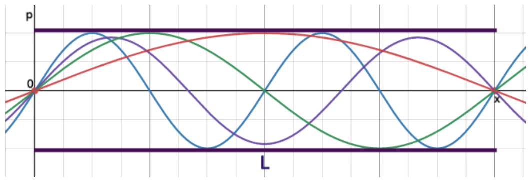

Figure 3: Superposition of the first four vibration modes corresponding to the pressure variation $p(x,t)$ in a tube of length L.

a digital waveguide consists of two digital delay lines that represent sampled traveling waves moving in opposite directions. This structure directly corresponds to the general solution of the one-dimensional wave equation, where the total displacement is expressed as the sum of a right-going and a left-going wave component. Furthermore, this approach is consistent with the modal solution of the wave equation for an open tube, as given by equation (3), since each sinusoidal mode can be understood as the result of two counter-propagating traveling waves that interfere to form a standing wave. As pointed out by [4], wind instruments—including the Colombian gaita—can be effectively simulated using digital waveguide models.

To implement this physically grounded representation in the digital domain, it is necessary to discretize the wave equation. The behavior of wave propagation inside an open cylindrical tube—such as the Colombian gaita—can thus be modeled by translating the continuous formulation into a discrete-time system. According to [5], this is achieved by sampling the amplitudes of the traveling waves at regular time intervals T, with a corresponding sampling rate $f = 1/T$. The spatial and temporal domains are discretized using m spatial samples and n temporal samples, such that:

$$x \to x_m = mX \tag{4}$$
$$t \to t_n = nT \tag{5}$$

Applying this discretization to the general solution of the wave equation yields:

$$\begin{aligned} y(t_n, x_m) &= y_r\left(t_n - \frac{x_m}{c}\right) + y_\ell\left(t_n + \frac{x_m}{c}\right) && (6)\\ &= y_r(nT - mX/c) + y_\ell(nT + mX/c) && (7)\\ &= y_r[(n-m)T] + y_\ell[(n+m)T], && (8)\end{aligned}$$

where c denotes the speed of sound.

The term

$$y_r[(n-m)T] = y^+(n-m) \tag{9}$$

can be interpreted as the output of a delay line of m samples, with input $y^+(n)$. A delay of m samples in the time index corresponds to a wave propagating to the right, while an advance of m samples represents a left-traveling wave [5, p. 76].

Thus, the discretized solution becomes:

$$y(t_n, x_m) = y^+(n-m) + y^-(n+m) \tag{10}$$

This discrete formulation mirrors the continuous standing wave solution previously derived from the modal expansion of the wave equation. Each standing wave mode can be interpreted as the result of two counter-propagating traveling waves interfering within the tube. Therefore, the digital waveguide framework not only offers computational efficiency but also maintains a strong correspondence with the physical principles governing sound propagation in wind instruments. As highlighted by [6], any ideal one-dimensional waveguide can be effectively simulated using this approach.

As noted by [7], the two variables commonly used in the simulation of acoustic tubes through digital waveguides are pressure and volume velocity. Accordingly, the Ohm's law relationships for the tube's acoustic variables are given by:

$$p^+(n) = Z_c u^+(n) \tag{11}$$

$$p^-(n) = -Z_c u^-(n) \tag{12}$$

where p^+ and p^- are the pressure components propagating to the right and to the left, respectively; u^+ and u^- are the volume velocity components propagating to the right and to the left, respectively; and Z_c is the characteristic impedance of the tube, defined as:

$$Z_c = \frac{\rho c}{A} \tag{13}$$

with ρ being the air density, c the speed of sound in air, and A the cross-sectional area of the tube.

According to [8], the reflectance observed from the entrance of a cylindrical tube of length L is given by:

$$\mathcal{R}(Z_L) = e^{-2jkL}\left[\frac{Z_L - Z_c}{Z_L + Z_c}\right] \tag{14}$$

where Z_L is the load impedance at $x = L$. The total reflected intensity at Z_L is expressed as $\mathcal{R}^2$ [3, p. 197], as follows:

$$\begin{aligned} \mathcal{R}^2(Z_L) &= \left(e^{-2jkL}e^{2jkL}\right)\left[\frac{Z_L - Z_c}{Z_L + Z_c}\right]^2 && (15)\\ &= \left[\frac{Z_L - Z_c}{Z_L + Z_c}\right]^2 && (16)\end{aligned}$$

This shows that there is no reflection if $Z_L = Z_c$, and total reflection occurs if $Z_L = 0$ or $Z_L = \infty$. The open end of a cylindrical tube is usually poorly represented by a load impedance $Z_L = 0$. However, the acoustic properties at the open end of a tube are more accurately characterized by a non-zero and complex-valued load impedance $Z \neq 0$ [8, p. 103]. Figure 4 illustrates the implementation of pressure wave propagation in a cylindrical tube using a digital waveguide. At $x = L$, the reflectance is $\mathcal{R}_L(z)$.

Then, following [8] and [7], this waveguide structure can be simplified by limiting the observation point of

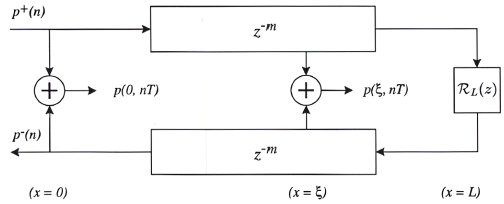

Figure 4: Implementation of plane wave propagation in a cylindrical tube using a digital waveguide. The symbol z^{-m} represents the delay of m samples (from [8]).

the physical pressure to the beginning of the tube (i.e., the orifice entrance). In this way, it is possible to use a single delay line, and the digital filter representing $\mathcal{R}(z)$ can be moved across the lower delay line due to linearity and time invariance. This process is illustrated in Figure 5.

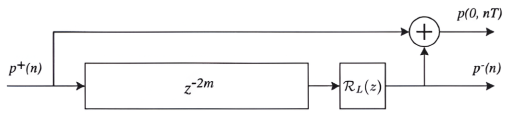

Figure 5: Simplified implementation of plane wave propagation in a cylindrical tube, neglecting viscothermal losses. The observation point is restricted to the tube entrance (from [8]).

4.0.1. STK instruments

The Synthesis ToolKit (STK) is a set of audio signal processing and synthesis classes written in open-source C++ code. According to the authors, this library was designed to facilitate the development of musical synthesis and audio processing software. Being a cross-platform library, it can be used on different operating systems such as Windows, Linux, and macOS. One of the most important features of STK is the ability to control its classes in real time, allowing users to interact with audio signals instantly [9].

STK includes the *Flute* class, which employs physical modeling by digital waveguide to generate sounds in which the actual acoustic wave-generating mechanism is an open tube, as in the case of the Western concert flute or the Colombian gaita. In the work titled *Sound Synthesis of a Colombian Gaita by Means of Physical Modeling* [7], the author acoustically analyzes the Colombian gaita and performs various physical measurements related to impedance and reflectance, concluding that digital waveguide modeling is useful for synthesizing the timbre of the gaita. Furthermore, [7] uses the open tube model from STK to synthesize the Colombian gaita, creating a graphical interface in the JUCE platform [10], in which specific physical parameters that alter the timbre and pitch of the synthesized sound can be modified.[2]

[2]Special thanks to Camilo Gómez Bonilla for sharing with us the gaita plugin he developed in JUCE.

4.1. Application in MAX/MSP

4.1.1. PeRColate Library

As stated by [11], PeRColate is an open-source distribution of various synthesis and audio processing algorithms designed for Max, MSP, and Nato. PeRColate[3] is a collection of 63 objects based on physical models, modal synthesis, PhiSM, MaxGens, SID, Random DSP, among others. It contains partial adaptations of the STK library, providing real-time sonic interaction functions; one such adaptation is the *flute∼* object for Max/MSP [12], which uses digital waveguide physical modeling as its synthesis technique.

The *flute∼* object uses a waveguide model, in which delay lines simulate the wave properties present in air vibration inside an open tube. The following are modifiable parameters of the object:

- **Breath pressure:** related to the blowing intensity.
- **Jet delay:** related to the physical distance the airstream travels from the mouth to the entry point of the tube. According to [7], this parameter can modify the modes of oscillation that are excited in the tube.
- **Noise gain:** noise present in the sound (as discussed in Chapter 1, this noise results from several physical factors such as the air circulating inside the tube).
- **Vibrato frequency:** related to pressure fluctuations in the breath.
- **Vibrato amount:** related to the intensity of those fluctuations.
- **Audible frequency:** related to the tube length and thus to the musical pitch produced.

4.1.2. Testing in MAX/MSP

As noted by [7], the STK open tube model is useful for modeling the Colombian gaita; therefore, the code from the *flute∼* object is useful for describing the parameters of this Colombian instrument. Tests were conducted in MAX/MSP by modifying the parameters of the *flute∼* object based on the values proposed by Gomez (2012, p.66) and comparing, through perception, with the timbre of the actual gaita. By modifying the parameters, it was observed that it is possible to generate a sound timbre very similar to that of the Colombian gaita. Since the code of PeRColate objects is open-source, it was possible to set parameters that achieved greater affinity with the gaita's timbre, resulting in the creation of the *gaitacol∼* object.[4]

Two acoustic gaitas were used for comparison: one made of cardón wood and one made of aluminum. Although the synthesized gaita sound was not identical, it was quite similar, and thus considered a satisfactory result. The following links present three examples comparing the real Colombian gaita with the one synthesized using the open tube model from PeRColate.

[3]Available at `https://github.com/Cycling74/percolate`
[4]Available at `https://github.com/jufvasquezri/Codigo-Gaita`

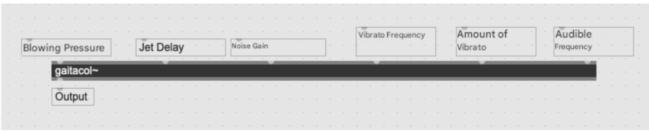

Figure 6: Parameters of each *inlet* in the *gaitacol*∼ object

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- Cardón gaita and synthesized version: `https://www.youtube.com/watch?v=vnBa9CzXIdk`
- Aluminum gaita and synthesized version: `https://www.youtube.com/watch?v=QRj33Dpio0c`
- Aluminum gaita and synthesized version: `https://www.youtube.com/watch?v=4jw6lqBTOsA`

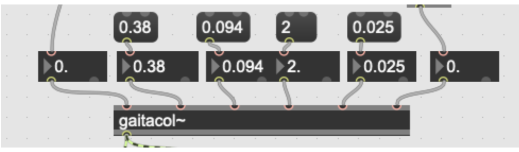

Figure 7: A possible *preset* of the *inlet* parameters for the *gaitacol*∼ object

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According to the tests conducted and based on perceptual comparison, a preset that produced a timbre similar to the Colombian gaita is presented in Figure 7. However, other *presets* can be explored using the following recommended parameter ranges from the tests:

- **Breath pressure:** (0.0 – 1.0)
- **Jet delay:** (0.0 – 1.0)
- **Noise gain:** (0.0 – 1.0)
- **Vibrato frequency:** (0 – 4)
- **Vibrato amount:** (0 – 1)

Figure 8 presents a patch demonstrating one possible use of the *gaitacol*∼ object, in which a cascading filter is added to expand the possibilities for timbral modification.

Since the parameters of the object are related to the actual interaction between the performer and the instrument, it is possible to use an interface such as a MIDI controller for real-time manipulation.

5. Analysis of the Sonic Result

5.1. Spectrogram

Figure 9 shows a comparison between the spectra of the synthesized gaita and the real cardón gaita,[5] both playing the fundamental pitch **B** (495 Hz). In this spectrogram, it is possible to observe the noise profile of both sounds across the full frequency range from 0 to 20,000 Hz. Figure 10 presents the same comparison limited to the range of 0 to 5,300 Hz, allowing a more detailed visualization of the harmonic behavior. Although the noise profile and harmonic structure are similar in both the synthesized and the real gaita signals, differences can be observed in the higher frequency register of the spectrograms. These findings are consistent with the observations of [7], who states that, while the modeled instrument and the real one converge in the basic timbral attributes, there are discrepancies in the magnitude of higher harmonics and the general noise content.

Although the timbre resulting from the synthesis using the *gaitacol*∼ object is quite similar to that of the acoustic instrument, real-time control of the parameters is not very effective when manipulated via a computer keyboard. Given the physical structure of the gaita, it would be more appropriate to use a controller whose form resembles that of a wind instrument.

5.2. Spectral Centroid

The **Spectral Centroid** audio descriptor measures the barycenter of a sound's energy distribution and is expressed in *Hertz* (Hz)[13]. Mathematically, it is calculated as the weighted average of the frequencies present in the

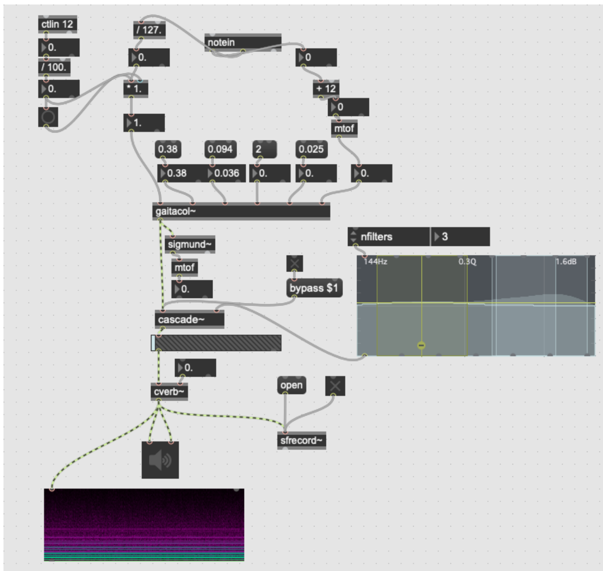

Figure 8: Patch using the *gaitacol*∼ object.

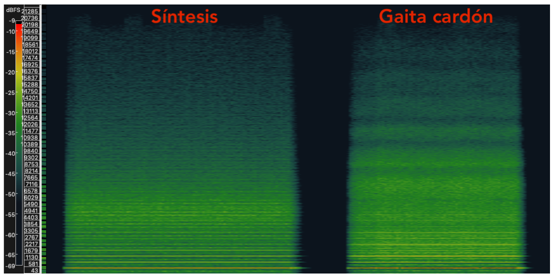

Figure 9: Sound spectrum of the synthesis and the cardón gaita in the 0–20,000 Hz range.

[5] Recorded at the *Núcleo Interdisciplinar de Comunicação Sonora* (NICS).

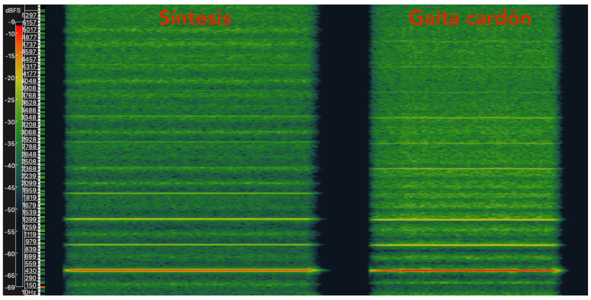

Figure 10: Sound spectrum of the synthesis and the cardón gaita in the 0–5,300 Hz range.

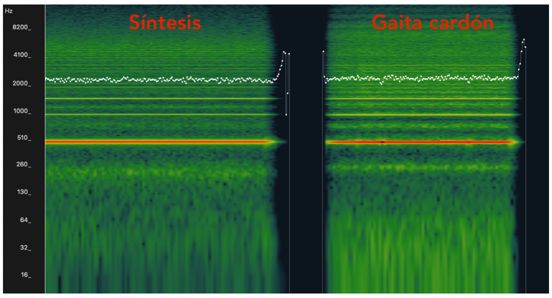

Figure 11: Spectral centroid of the synthesis and the cardón gaita playing the fundamental pitch B4.

signal:

$$C_{(i)} = \frac{\sum_{k=1}^{k} k \times |X_i(k)|^2}{\sum_{k=1}^{k} |X_i(k)|^2} \quad (17)$$

where $X_i(k)$ represents the magnitude values of the spectrum obtained through an FFT,[6] and k corresponds to half the number of spectral components used in the transformation. In psychoacoustic terms, $C_{(i)}$ is associated with the perception of brightness in a given frequency region [13, p. 206].

Using the Spectral Centroid descriptor[7] it was found that, although the energy distribution across the spectrum is not identical, both centroid values are located within a similar frequency region. As shown in Figure 11, the centroid of the synthesized gaita is located around 2,300 Hz (approximately **D7**), while the centroid of the real gaita is around 2,500 Hz (approximately **D#7**). This is consistent with the fact that the fifth harmonic of the fundamental pitch **B4** corresponds approximately to **D#7–14c**.

6. Compositional Process

6.1. Patch in MAX/MSP

A patch[8] was created in MAX/MSP with two main functions: sound processing and sound synthesis.

Sliders were used to control 8 parameters:

- Volume of the real gaita.
- Volume of the transposed real gaita, processed by the *pitch shifter* object.
- Reverberation of the real gaita, with a minimum duration of 0 seconds and a maximum of 20 seconds. Reverberation was implemented using the **jc_verb**~ object from the PeRColate library.
- Reverberation of the transposed real gaita, with a minimum duration of 0 seconds and a maximum of 10 seconds.
- Volume of the physically modeled gaita synthesis (*gaitacol*~ object).
- Volume of the transposed gaita synthesis, processed by the *pitch shifter* object.
- Reverberation of the gaita synthesis, with a minimum duration of 0 seconds and a maximum of 5 seconds.
- Reverberation of the transposed gaita synthesis, with a minimum duration of 0 seconds and a maximum of 5 seconds.

6.2. Synthesis

The subpatch **p gaita** was created, which contains the *gaitacol*~ object with the parameters defined in Figure 8. Additionally, a graphic equalizer with cascading filters was used to process the signal generated by the gaita synthesis. This allowed for easier timbral shaping in order to achieve the desired gaita sound.

The gaita synthesis was triggered in two ways:

- The *sigmund*~ object[9], created by Miller Puckette, was employed to identify the frequencies present in a sound. This object was used to detect the pitch produced by the real gaita and replicate it through the synthesis object.
- A free MIDI controller for tablets running iOS[10], was used to produce specific pitches through the synthesis object, as shown in Figure 8 (see Figures 12 and 13).

Figure 12: Application used to control MIDI pitch.

6.3. Structure and Poetics of the Composition

The composition ***Entre tanto y tanto, un caminar continuo*** seeks to explore the delicate interplay between ancestral knowledge and contemporary technological practices. It proposes a poetic meditation on the convergence

[6] FFT: *Fast Fourier Transform*, which, according to [13], is the operation that computes the magnitude and phase values of a segmented input signal, calculated for each time window.

[7] Developed by Jamie Bullock, available at https://github.com/jamiebullock/LibXtract

[8] Available at https://drive.google.com/drive/folders/19WquDh_CeZowPyFSh3HZwVq9O300L5iv?usp=sharing

[9] Available at https://music.arts.uci.edu/dobrian/maxcookbook/pitch-tracking-sigmund

[10] *Midi Controller Pro* app, available at https://apps.apple.com/tr/app/midi-controller-pro/id594785451

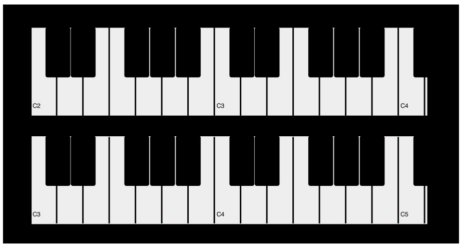

Figure 13: Tablet MIDI keyboard used to perform gaita synthesis.

of two worlds often perceived as oppositional: the traditional, embodied in the sound of the Colombian gaita, and the technological, represented by digital synthesis and sound processing. This work suggests that rather than being in conflict, these realms can coexist in a space of mutual transformation and creative expansion. The gaita was performed by Juan Sebastián Muñoz (1996), a Colombian flutist and music graduate from the Universidad Pedagógica Nacional (Colombia). The complete work can be accessed at the following link: `https://youtu.be/WoMS1__5Ons?si=YuYAd8Itw0SkKLWd`

Structured as a sonic ritual, the piece unfolds gradually, allowing the listener to witness the transformation of sound as both a material and symbolic journey. The real gaita, with its breath, imperfections, and resonance rooted in centuries of cultural tradition, dialogues with its digital counterpart—a synthesis that begins as imitation but eventually grows into an autonomous voice. The path of the composition mirrors a narrative of growth and integration, culminating in a shared space where both the real and the synthetic are in constant interaction. The form of the piece is articulated through five interconnected sections:

- **A. Root (Raíz):** The piece opens with the unprocessed voice of the acoustic gaita, serving as a sonic invocation of origin. This section is characterized by melodic gestures that arise naturally from the gaita's physical construction and traditional playing technique—its characteristic intervals, breath-driven phrasing, and ornamental articulation. Here, the gaita is presented in its most unaltered form, embodying cultural memory and grounding the listener in a soundscape that feels at once familiar and sacred. This sonic root is not merely a point of departure, but a persistent reference throughout the piece, anchoring all that follows.
- **B. Echoes (Ecos):** As the piece progresses, the gaita begins to be processed digitally. Through subtle use of pitch shifting, reverberation, and spatialization, its sound becomes layered and extended. These digital treatments function as acoustic reflections—echoes that reverberate outward from the source instrument, diffusing it into new dimensions. The transformation is not abrupt, but gradual, allowing the listener to sense a shifting presence that retains the essence of the original sound while expanding its expressive range. In this section, technology does not overwrite tradition; instead, it illuminates it from within, suggesting new interpretative paths. The gaita and its echo engage in a call-and-response that blurs the line between the source and its digital double.
- **C. Metamorphosis (Metamorfosis):** A turning point in the piece, this section introduces the digitally synthesized gaita, generated through physical modeling. Initially, this synthetic voice mimics the melodic material of the real gaita, creating a sense of shadowing or doubling. However, the imitation is imperfect: the synthetic line is transposed, displaced, and at times distorted, suggesting both a tribute and a departure. The result is a layered counterpoint between the real and the artificial, a sonic metaphor for the process of cultural adaptation and technological mediation. The synthetic gaita begins to assert itself—not as a replica, but as a transforming body, shaped by the very act of imitation. This metamorphosis speaks to the tensions and possibilities of creating with tools that do not originate in the tradition, but that can still engage it meaningfully.
- **D. Digital Dance (Danza Digital):** Having acquired expressive independence, the synthetic gaita no longer follows the real gaita's gestures. It begins to articulate its own musical ideas, exploring melodic paths that diverge from the traditional vocabulary. This section marks a moment of emancipation: technology, once a medium of reproduction, becomes a creative agent in its own right. The timbral palette expands, rhythmic structures become more complex, and the synthetic instrument takes the lead in shaping the musical discourse. Yet, rather than dominating or replacing the real gaita, this digital voice proposes a new form of listening—one in which the familiar is refracted through unfamiliar lenses. The "digital dance" thus becomes a celebration of autonomy and creative reinterpretation.
- **E. The Embrace (El abrazo):** In the final section, both voices—the acoustic and the synthetic—share the sonic stage with parity. No longer in opposition or hierarchy, they intertwine in rhythmic unison and contrapuntal dialogue. The gestures of the gaita are echoed and transformed by the synthetic voice, and vice versa. This interplay suggests not just coexistence, but interdependence. It is a musical "embrace" in which tradition and technology recognize each other not as rivals but as collaborators in a shared sonic ritual. The work concludes not with a resolution, but with a continued motion—*a continuous walk*—where sound becomes a space of encounter, memory, and becoming.

Ultimately, the composition proposes a rethinking of the boundaries between past and future, acoustic and digital, human and machine. By allowing these dimensions to converse rather than collide, ***Entre tanto y tanto, un caminar continuo*** affirms the transformative power of music as a space of convergence—where breath becomes algorithm, and tradition, a living process of invention.

7. Conclusions

This research set out to explore the acoustical behavior of the Colombian gaita and translate this understanding into a digital synthesis model that could interact musically with the acoustic instrument in a new composition. The outcome is a creative and technical synthesis of knowledge drawn from acoustics, physical modeling, and compositional practice. The project demonstrates how traditional musical practices can be reimagined and expanded through digital technologies without displacing their cultural significance.

The first phase of the project involved a detailed study of the construction and acoustic principles of the gaita. Understanding how the physical characteristics of the instrument determine its sound led to the derivation of a wave equation that models its behavior. This acoustic modeling provided the foundation for developing a synthesis tool that could recreate the instrument's unique timbre through digital waveguide modeling.

Based on this research, the object *gaitacol*∼ was implemented in MAX/MSP as a custom synthesis tool. It enabled real-time interaction with the gaita's digitally modeled sound. During testing and performance, some limitations became evident—most notably, the difficulty of reproducing upper harmonics by controlling simulated blowing pressure. This limitation confined the synthesis mainly to fundamental frequencies, suggesting a valuable area for future development in refining control parameters and enhancing the model's expressivity.

The synthesis was then integrated into the composition *Entre tanto y tanto, un caminar continuo*, a piece designed to explore and reflect on the relationship between ancestral musical knowledge and technological tools. Structured in five sections, the composition traces the evolving interaction between the acoustic and synthesized gaita, from imitation and transformation to mutual dialogue. The work acts as a sonic metaphor for the coexistence of traditional and technological modes of musical expression.

Throughout the development of the synthesis model and the composition, auditory analysis tools such as spectral centroid and spectrograms were used alongside perceptual listening to evaluate and refine the synthesized sound. While full replication of the gaita's rich acoustic complexity remains a challenge, the model captured essential features of its timbre, allowing the digital voice to be recognized and accepted within the musical context.

Beyond its technical achievements, this work offers a broader reflection on the role of traditional instruments in contemporary creative practices. It proposes an alternative approach to musical pedagogy, one that values diverse instrumental traditions and seeks to incorporate them into academic curricula alongside Western canonical instruments. Such integration would not only enrich musical education but also challenge homogenizing tendencies in institutionalized music-making.

In conclusion, this project contributes to a growing body of research that seeks to bridge cultural heritage and technological innovation. It shows that digital tools, when used thoughtfully and respectfully, can extend the expressive potential of traditional instruments without erasing their identity. The work invites further exploration of how physical modeling synthesis and interactive media can be used to preserve, transform, and revitalize sonic traditions. *Entre tanto y tanto, un caminar continuo* is both a culmination and a beginning—an example of how personal, scientific, and artistic pathways can converge in a continuous journey of sound.

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