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Synthesizing Tradition: Physical Modeling and Composition with the Colombian Gaita

Sintetizando a Tradição: Modelagem Física e Composição com a Gaita Colombiana

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Abstract: This article focuses on the physical modelling of the Colombian gaita using waveguide synthesis techniques. Based on an acoustic analysis of the instrument, including its timbral characteristics and resonant behaviour, the *gaitacol~* object was developed in the MAX/MSP environment to simulate its sound in real time and enable expressive interaction. The resulting synthesis was integrated into the composition *Entre tanto y tanto, un caminar continuo* (2024), a live-electronic work that explores the convergence of traditional sound and contemporary music technologies. The article explains and analyzes the composition in its five sections – *Raíz*, *Ecos*, *Metamorfosis*, *Danza digital*, and *El abrazo* – addressing the different ways in which the acoustic gaita interacts with digital signal processing and sound synthesis. These sections articulate contrasting modes of dialogue, including timbral reinforcement, spectral transformation, rhythmic interaction, and hybrid textures that blur the boundaries between acoustic and digital sound. This work contributes to the field of computer music by applying physical modelling techniques to a non-Western instrument, and to the field of mixed composition by proposing

compositional strategies for integrating traditional instruments into contemporary creative contexts.

Keywords: colombian gaita. sound synthesis. physical modeling. musical composition. live-electronic music.

Resumo: Este artigo concentra-se na modelagem física da gaita colombiana por meio de técnicas de síntese por guias de onda. Com base em uma análise acústica do instrumento, incluindo suas características tímbricas e comportamento ressonante, o objeto *gaitacol~* foi desenvolvido no ambiente MAX/MSP para simular seu som em tempo real e possibilitar uma interação expressiva. A síntese resultante foi integrada à composição *Entre tanto y tanto, un caminar continuo* (2024), uma obra mista que explora a convergência entre o som tradicional e as tecnologias musicais contemporâneas. O artigo explica e analisa a composição em suas cinco seções – *Raíz*, *Ecos*, *Metamorfosis*, *Danza digital* e *El abrazo* – abordando as diferentes formas de interação entre a gaita acústica, o processamento digital de sinais e a síntese sonora. Essas seções articulam modos contrastantes de diálogo, incluindo reforço tímbrico, transformação espectral, interação rítmica e texturas híbridas que desfazem os limites entre o som acústico e o digital. Este trabalho contribui para o campo da música computacional ao aplicar técnicas de modelagem física a um instrumento não ocidental, e para o campo da composição mista ao propor estratégias composicionais para a integração de instrumentos tradicionais em contextos criativos contemporâneos.

Palavras-chave: *g*aita colombiana. *s*íntese sonora. modelagem física. *c*omposição musical. música mista.

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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 article presents a research project that combines acoustic analysis, sound synthesis, and musical composition, focusing on the *gaita colombiana*. The study aims to investigate the instrument's physical and acoustic behavior and to apply physical modelling 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. In addition to the technical aspects, the article also addresses the compositional process of the piece *Entre tanto y tanto, un caminar continuo (*2024), a composition for *Colombian gaita* and live electronics, focusing on the interactions, dialogue, and mutual development between the acoustic gaita and its synthesized counterpart. The work explores how the real and virtual instruments influence each other in performance, shaping the musical form, timbral evolution, and expressive possibilities of the piece.

By integrating traditional acoustics, digital technology, and creative composition, this work contributes to the mixed music repertoire by incorporating traditional instruments into a contemporary electroacoustic context, expanding their expressive and artistic possibilities through physical modeling synthesis.

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* (ASCENSIÓN GÓMEZ BLANCO, 2016).

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 (OCHOA ESCOBAR, 2013, 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) (OCHOA ESCOBAR, 2013, 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 millimetres thick. The length of the tube was historically tailored to the arm length of the player, ensuring ergonomic comfort (OCHOA ESCOBAR, 2013, 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 (OCHOA ESCOBAR, 2013, 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 airflow. 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 (OCHOA ESCOBAR, 2013).

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 channelled 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 (OCHOA ESCOBAR, 2013, 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).

Figure 1 - Pair of aluminum gaitas.

Source: photograph by the author.
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.

According to Ochoa Escobar (2013), modern gaitas may be constructed from alternative materials such as aluminium, 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 aluminium or PVC, produce a cleaner sound, whereas the natural *cardón* surface contains fibrous material that adds a "dirty" or noisier quality to the tone (OCHOA ESCOBAR, 2013, 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 (OCHOA ESCOBAR, 2013).

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:

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

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 (FLETCHER; ROSSING, 2012).

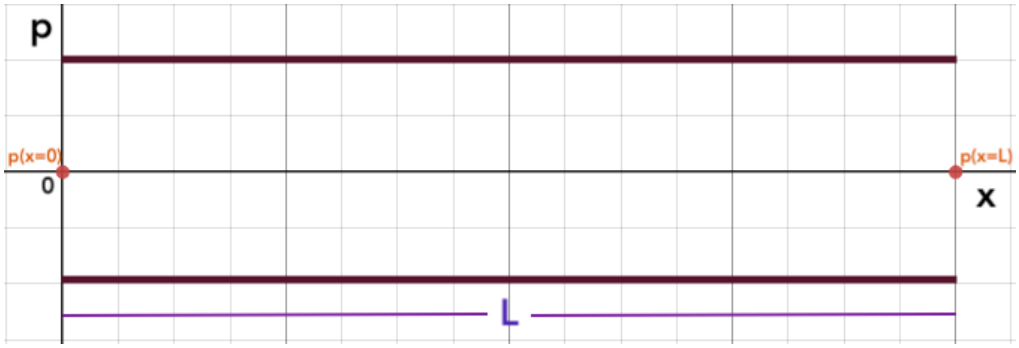
It is possible to consider the wave equation in the physical context of an open tube, as is the case for the Colombian gaita. Let us suppose a tube of length L, open at both ends. Due to the boundary conditions on the tube, there should be no pressure variation at its ends; that is, the pressure inside 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

$$p(0,t)=p(L,t)=0 \tag{2}$$

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.



Source: Vásquez Rincón (2024).
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:

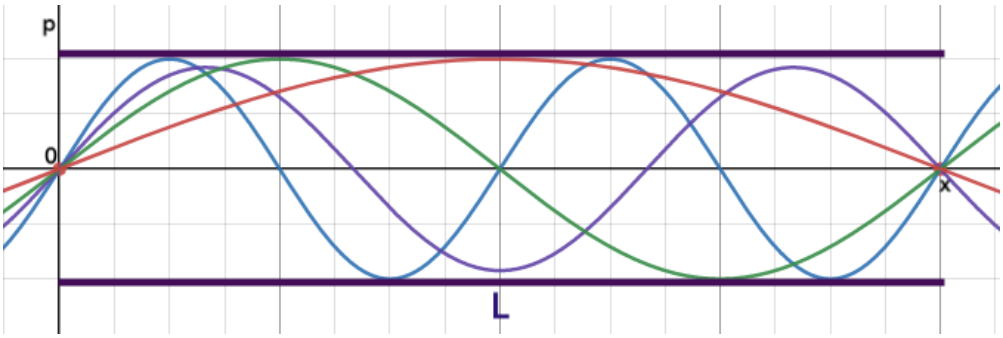
$$p(x,t)=\sum_{n=1}^{\infty} D_n \sin\left(\frac{n\pi}{L}x\right)\sin\left(\frac{n\pi}{L}ct\right) \tag{3}$$

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 $\omega_n=n\pi c/L$. 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 $p(x,t)$.

Figure 3 - Superposition of the first four vibration modes



Source: Vásquez Rincón (2024).
Superposition of the first four vibration modes corresponding to the pressure variation p(x,t) in a tube of length L.

4. Modelling 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, 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 noted by Roads (1996, p. 282), wind instruments—including tube instruments—can be effectively simulated using digital waveguide models.

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

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 can thus be modeled by translating the continuous formulation into a discrete-time system. According to Smith (1992), this is achieved by sampling the amplitudes of the traveling waves at regular time intervals T with a corresponding sampling rate $f=\frac{1}{T}$. The spatial and temporal domains are discretized using m spatial samples and n temporal samples, such that:

$$x \rightarrow x_m = mX \tag{4}$$

$$t \rightarrow t_n = nT \tag{5}$$

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

$$y(t_n, x_m) \quad ¿\, y_r\left(t_n - \frac{x_m}{c}\right) + y_l\left(t_n + \frac{x_m}{c}\right) \tag{6}$$

$$¿\, y_r(nT - mX/c) + y_l(nT + mX/c) \tag{7}$$

$$¿\, y_r[(n-m)T] + y_l[(n+m)T] \tag{8}$$

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 (SMITH, 1992, p. 76).

Thus, the discretized solution becomes:

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

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 noted by Gómez Bonilla (2020), 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 Scavone (1997), the reflectance observed from the entrance of a cylindrical tube of length L is given by:

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

where Z_L is the load impedance at $x = L$.

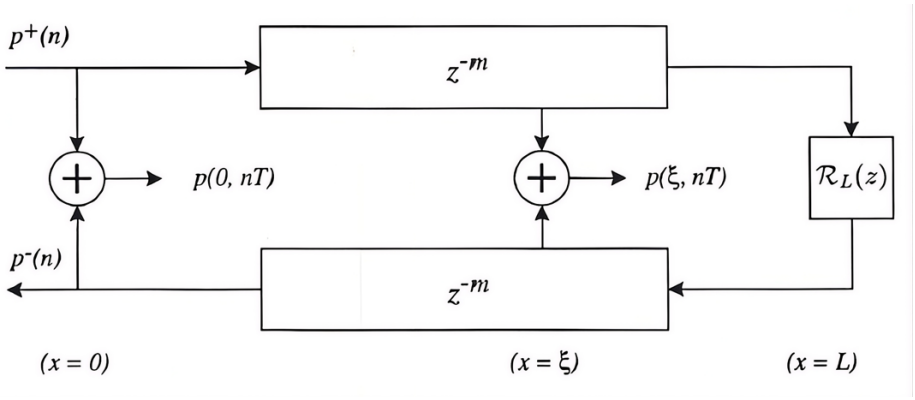
The total reflected intensity at Z_L is expressed as R^2 (FLETCHER; ROSSING, 2012, p. 197), as follows:

$$R^2(Z_L) = \left(e^{-2jkL}\, e^{2jkL}\right)\left[\frac{Z_L - Z_c}{Z_L + Z_c}\right]^2 \tag{15}$$

$$¿\left[\frac{Z_L - Z_c}{Z_L + Z_c}\right]^2 \tag{16}$$

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 $Z \neq 0$ (SCAVONE, 1997, 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 $R_L(z)$.

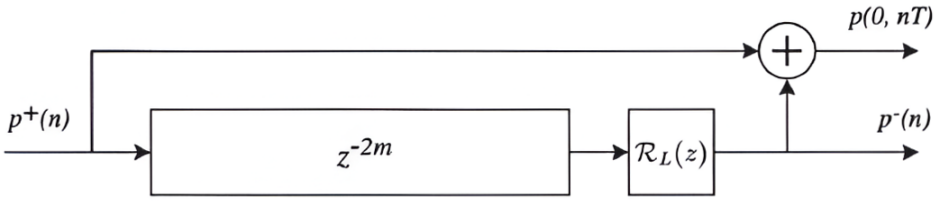
Figure 4 - Digital waveguide model of plane wave propagation in a cylindrical tube.



Source: Adapted from Scavone (1997)
Implementation of plane wave propagation in a cylindrical tube using a digital waveguide. The symbol represents the delay of m samples.

Then, following Scavone (1997) and Gómez Bonilla (2020), this waveguide structure can be simplified by limiting the observation point of 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 $R(z)$ can be moved across the lower delay line due to linearity and time invariance. This process is illustrated in Figure 5.

Figure 5 - Simplified digital waveguide model of a cylindrical tube.



Source: Adapted from Scavone (1997)
Simplified implementation of plane wave propagation in a cylindrical tube, neglecting viscothermal losses. The observation point is restricted to the tube entrance

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 (COOK; SCAVONE, 1999).

STK includes the *Flute* class, which employs physical modelling by digital waveguide to generate sounds in which the actual acoustic wave-generating mechanism is an open tube. In the work titled *Sound Synthesis of a Colombian Gaita by Means of Physical Modeling* (GÓMEZ BONILLA, 2020), the author acoustically analyses 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, Gómez Bonilla (2020) uses the Flute model from STK as a framework for constructing a physical modeling synthesis of the Colombian gaita, creating a graphical interface in the JUCE platform (PHILBERT, 2017), 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

As stated by Trueman and Dubois (2001), 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 (COLASANTO, 2010), 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 air jet travels from the mouth to the tube entrance. According to Gómez Bonilla (2020), this parameter can modify the modes of oscillation that are excited in the tube.
- Noise gain: noise present in the sound (this noise results from several physical factors such as the air circulating inside the tube and the material from which the tube is made).
- 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.

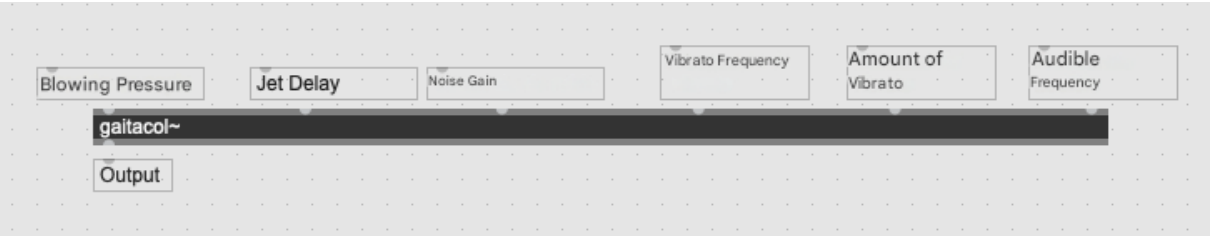
Testing in MAX/MSP

As noted by Gómez Bonilla (2020), the STK Flute model is useful for modelling 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

3 Available at https://github.com/Cycling74/percolate

by modifying the parameters of the *flute~* object (see Figure 6) based on the values proposed by Gómez Bonilla (2020, 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].

Figure 6 - Parameters of each *inlet* in the *gaitacol~* object.



Source: elaborated by the author.

Two acoustic gaitas were used for comparison: one made of *cardón* wood and one made of aluminium. 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.

- 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

4 Available at https://github.com/jufvasquezri/Codigo-Gaita

Figure 7 - A possible *preset* of the *inlet* parameters for the *gaitacol~* object.

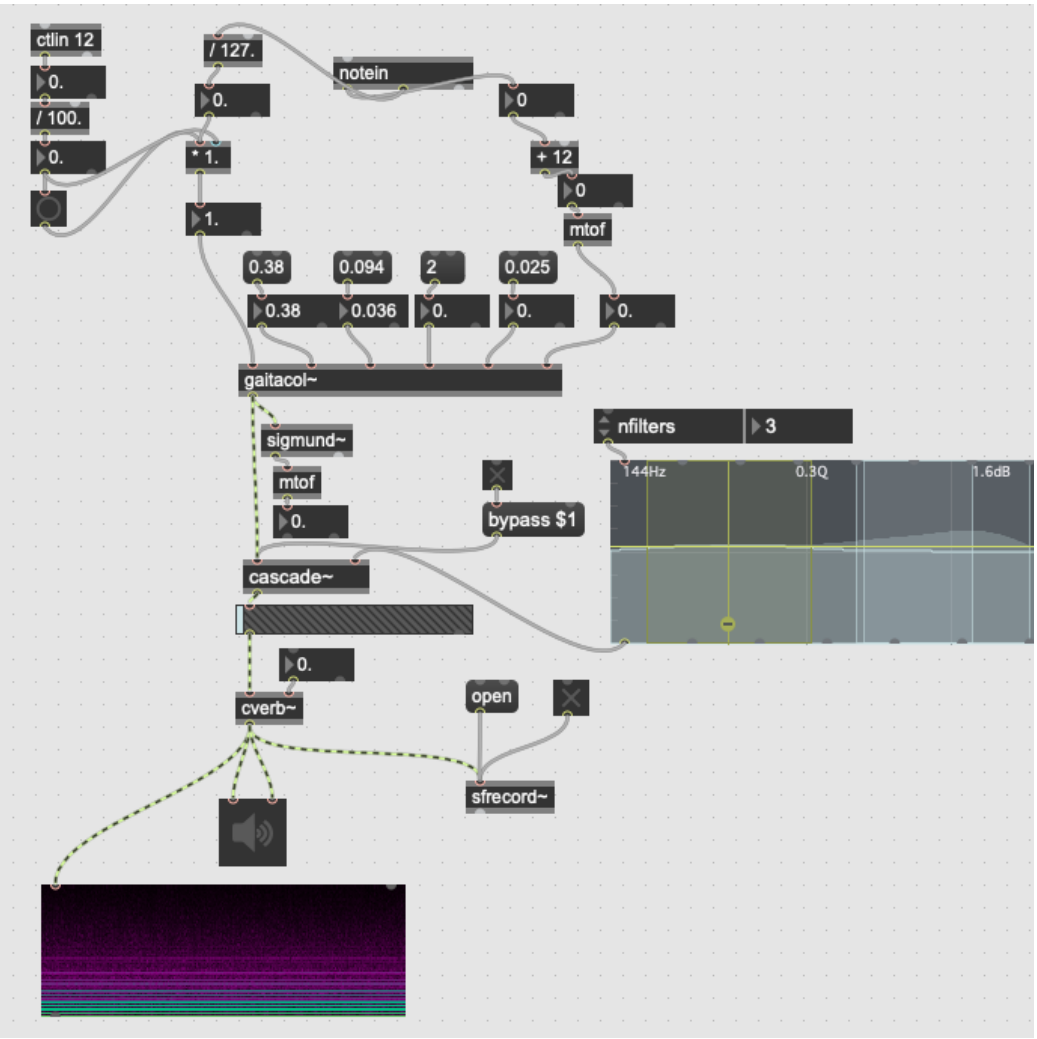
Source: elaborated by the author.

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) [At low air pressure, the sound is airy and has no defined pitch, whereas higher pressure produces an audible note.]
- Jet delay: (0.0–1.0) [This changes the harmonic content.]
- Noise gain: (0.0–1.0) [The noise content varies according to the material of the gaita and the thickness of its tube.]
- 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.

Figure 8 - Patch using the *gaitacol~* object.



Source: elaborated by the author.

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

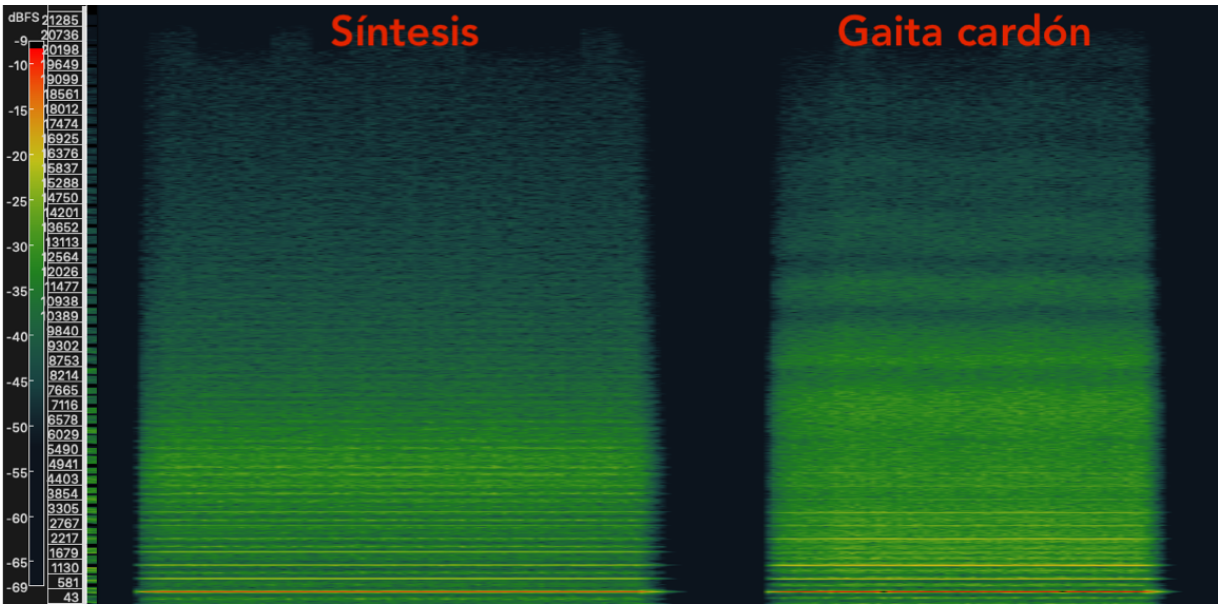
5.1 Spectrogram

Figure 9 shows a comparison between the spectra of the synthesized gaita and the real *cardón* gaita[5], both playing the

5 Recorded at the *Núcleo Interdisciplinar de Comunicação Sonora* (NICS) - *Universidade Estadual de Campinas* (UNICAMP).

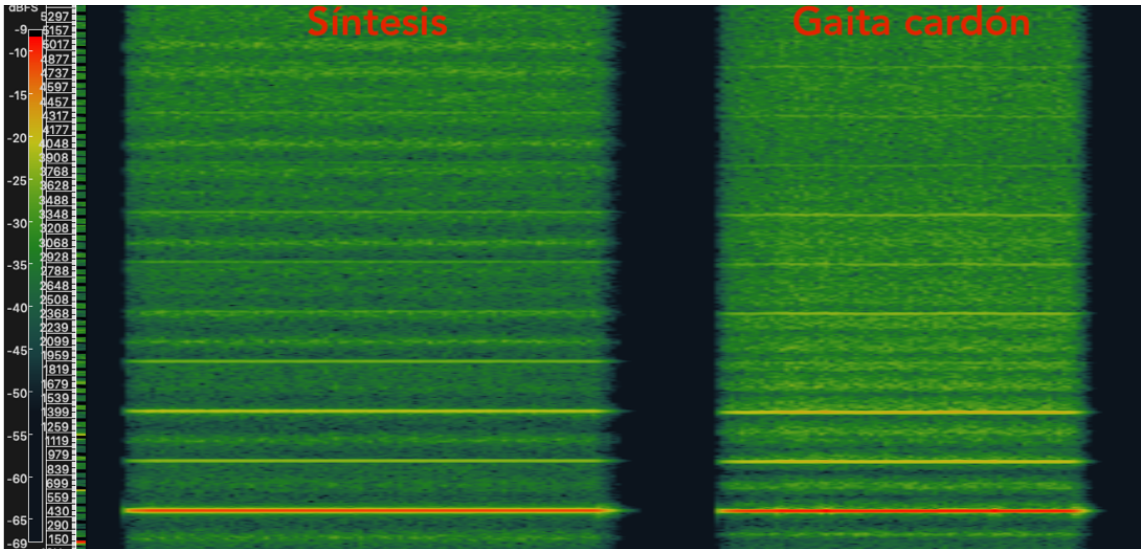
fundamental pitch **B** (495 Hz). In this spectrogram, it is possible to observe the noise profile of both sounds across the full frequency range from 0 to 20,000 Hz. Figure 10 presents the same comparison limited to the range of 0 to 5,300 Hz, allowing a more detailed visualization of the harmonic behavior. 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 Gómez Bonilla (2020), 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.

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



Source: Vásquez Rincón (2024).

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



Source: Vásquez Rincón (2024).

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) (ROSSETTI; MANZOLLI, 2017). Mathematically, it is calculated as the weighted average of the frequencies present in the signal:

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

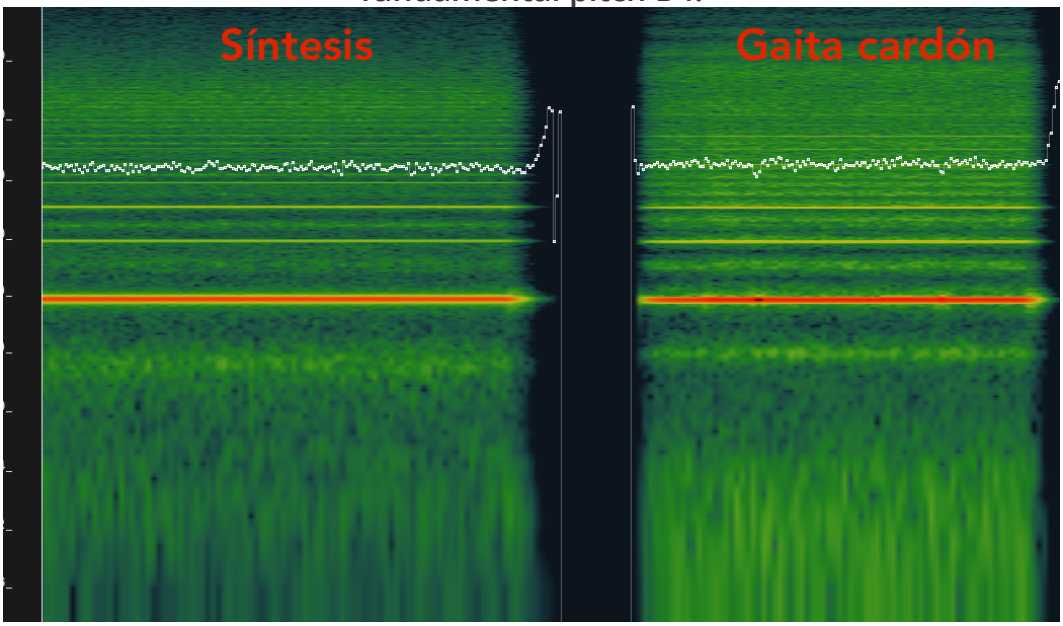
where $X_i(k)$ represents the magnitude values of the spectrum obtained through an FFT[6], and k corresponds to half the number of

6 FFT: Fast Fourier Transform, which, according to Rossetti and Manzolli (2017), is the operation that computes the magnitude and phase values of a segmented input signal, calculated for each time window.

spectral components used in the transformation. In psychoacoustic terms, $C_{|i|}$ is associated with the perception of brightness in a given frequency region (ROSSETTI; MANZOLLI, 2017, 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**. From a perceptual standpoint, this result can be interpreted as indicating that the real gaita exhibits slightly more energy in the higher-frequency range than the synthesized gaita. However, this observation corresponds to a specific *cardón* gaita, and it should be noted that the presence and distribution of noise may differ in gaitas made from other materials.

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



Source: Vásquez Rincón (2024).

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

6. Compositional Process

6.1 Patch in MAX/MSP

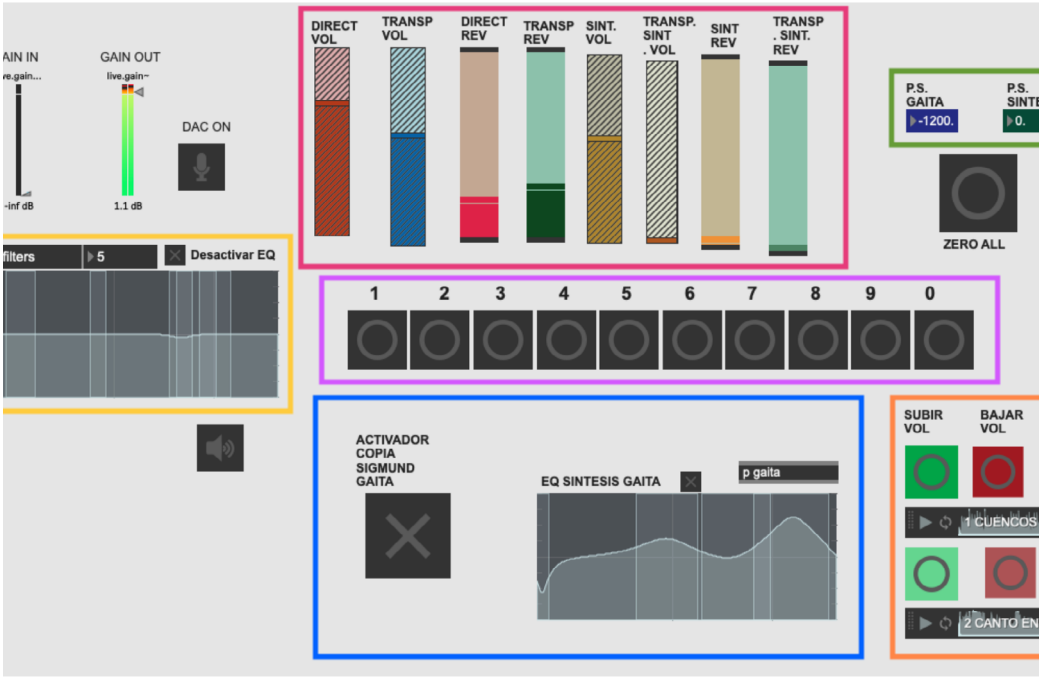
A patch[8] (see Figure 12) was created in MAX/MSP with two main functions: sound processing and sound synthesis.

Sliders (see Figure 13) 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.

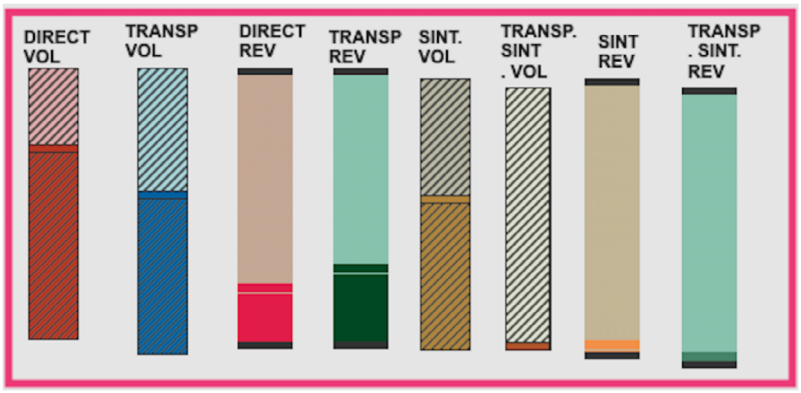
8 Available at https://drive.google.com/drive/folders/19WquDh_CeZowPyFSh3HZwVq9O300L5iv?usp=sharing

Figure 12- Graphical interface of the patch used in the piece.



Source: Vásquez Rincón (2024).

Figure 13 - Sliders used in the graphical interface of the patch for the piece.



Source: Vásquez Rincón (2024).

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.

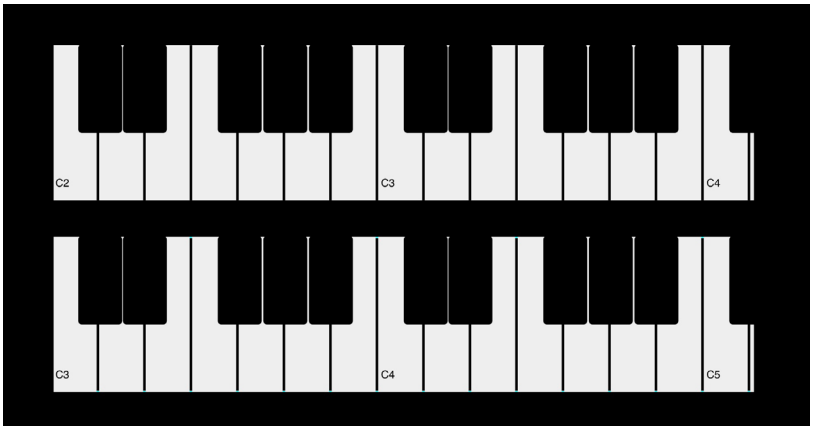
The gaita synthesis was triggered in two ways:

- 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 14 and 15).

Figure 14- Application used to control MIDI pitch.

Source: Apple Store.

Figure 15- Tablet MIDI keyboard used to perform gaita synthesis.



Source: elaborated by the author.

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

6.3 Structure and Poetics of the Composition

The composition *Entre tanto y tanto, un caminar continuo*[11] seeks to explore the delicate interplay between ancestral knowledge and contemporary technological practices. It proposes a poetic meditation on the convergence 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).

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:

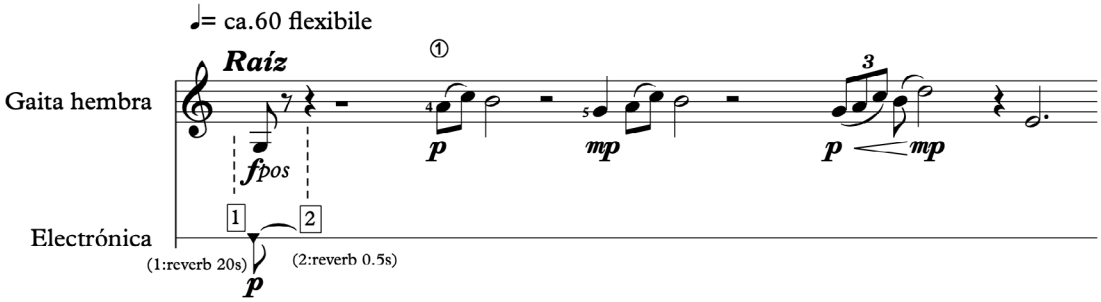
- **A. Root (Raíz)[12]:**

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

11 Available at: https://youtu.be/WoMS1__5Ons?si=YuYAd8Itw0SkKLWd
12 *Raíz*: https://youtu.be/WoMS1__5Ons?si=XVF01tKoHUB-RT0Q&t=8

throughout the piece, anchoring all that follows (An example is shown in Figure 16).

Figure 16- Opening of the piece, in the section *Raíz*.



Source: Vásquez Rincón (2024).

- **B. Echoes (Ecos)[13]:**

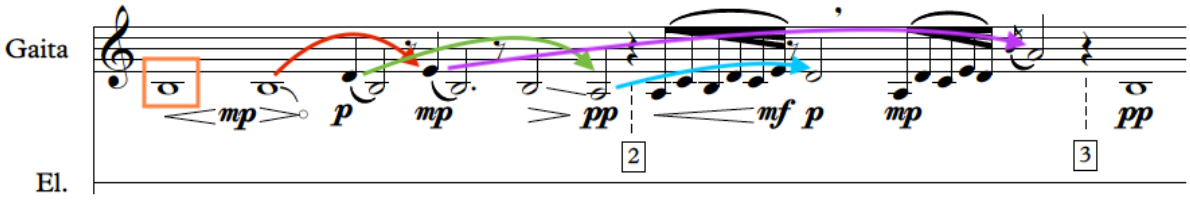
As the piece progresses, the gaita becomes increasingly shaped by digital processing. Through subtle applications of pitch shifting, reverberation, and spatialization, its sound expands into layered and resonant textures. These treatments function as acoustic reflections—echoes that radiate from the source instrument and project it into new sonic dimensions. The transformation unfolds gradually rather than abruptly, allowing the listener to perceive a shifting presence that preserves the essence of the original timbre while extending its expressive range. In this section, technology does not overwrite tradition; instead, it reveals it from within, opening alternative interpretative pathways. The gaita and its digitally generated echo engage in a call-and-response dynamic that blurs the boundary between the acoustic source and its mediated double.

This aesthetic gesture is articulated structurally in the *Ecos* section, which opens with an upward transposition of the real gaita by 498 cents. The interval—equivalent to a perfect fourth minus 2 cents (frequency ratio 4/3)—corresponds to the third interval of the harmonic series and establishes the harmonic framework for

13 *Ecos*: https://youtu.be/WoMS1__5Ons?si=qDHjawRxwI82NF9f&t=83

the ensuing dialogue. At the same time, the percussion enters, marking the beginning of the second stage of the ritual structure. As illustrated in Figure 17, the real gaita initially produces the pitch B3 (orange box), while the applied transposition simultaneously generates E4–2c. From this point onward, a network of sequential pitch relationships unfolds between the acoustic line and its transformed counterpart. For example, the sounding of B3 produces E4–2c through transposition, after which the acoustic instrument articulates E4 (red arrow), reinforcing the emerging connection. A similar process occurs with D4, first introduced by the real gaita (green arrow) and later reappearing as D4–2c through the transposition of A3. The section culminates with the acoustic production of D4 (blue arrow), establishing continuity with the pitch previously derived from the transposed A3. In this way, the technical procedure of transposition becomes the concrete mechanism through which the metaphor of echo and reflection is musically realized.

Figure 17- Melodic gestures with a 498-cent transposition and their sequential relationships.



Source: Vásquez Rincón (2024).

- **C. Metamorphosis (Metamorfosis)[14]:**

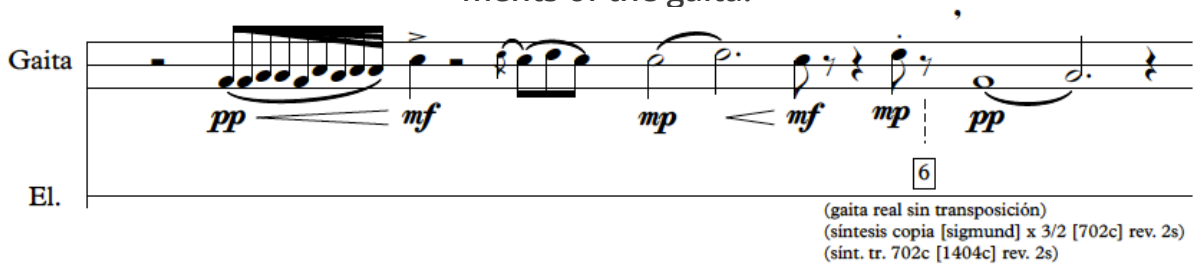
A turning point in the piece, this section introduces the digitally synthesized gaita, generated through physical modeling. Initially, this synthetic voice mimics the melodic material of the real gaita, creating a sense of shadowing or doubling. However, the imitation is deliberately imperfect: the synthetic line is transposed, displaced, and at times subtly distorted, suggesting both homage and divergence. The result is a layered counterpoint between

14 *Metamorfosis*: https://youtu.be/WoMS1__5Ons?si=3NUoYdPCCRpvYx3-&t=304

the acoustic and the digital, a sonic metaphor for processes of cultural adaptation and technological mediation. The synthesized gaita gradually asserts itself—not as a mere replica, but as a transforming body shaped through the very act of imitation. This metamorphosis reflects the tensions and possibilities inherent in creating with tools that do not originate within the tradition, yet are capable of engaging with it in meaningful ways.

From a structural and technical perspective, this section establishes the conditions for the emergence of the synthesis (see Figure 18). With the activation of bang 6, the digital instrument begins to reproduce in real time the melodic gestures performed by the acoustic gaita. This duplication, however, occurs 702 cents above the original line—corresponding to a perfect fifth plus 2 cents—thereby reinforcing the sense of displacement already suggested musically. Simultaneously, the synthesis itself is subjected to an additional upward transposition of 702 cents, extending the transpositional strategy introduced in the previous section through sound processing. In this way, the technical operations underpin and intensify the aesthetic gesture of transformation that defines this moment in the work.

Figure 18- Emergence of the synthesis (bang 6), copying the melodic movements of the gaita.



Source: Vásquez Rincón (2024).

- **D. Digital Dance (Danza Digital)[15]:**

In this section, the digital synthesis of the gaita abandons its initial role of imitation and undergoes a process of emancipation. Rather than reproducing the melodic movements dictated by the

15 *Danza Digital:* https://youtu.be/WoMS1__5Ons?si=7D4sRFisOOw-sV6e&t=575

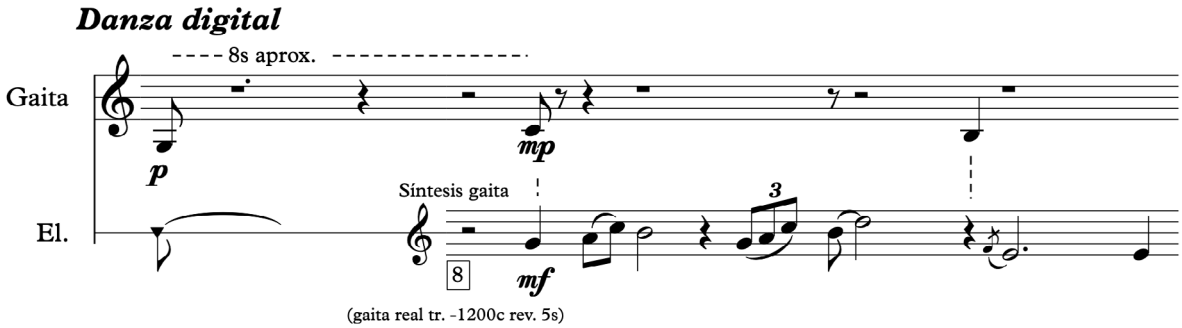
acoustic instrument, the synthesis begins to articulate its own melodic material, marking a clear turning point in the piece. As shown in Figure 19, these newly introduced gestures recall, in a transformed manner, melodic ideas presented by the gaita in the opening section. With the activation of bang 8, the real gaita is transposed downward by 1200 cents (one octave) and processed with a five-second reverberation, generating a sustained sonic background that supports and frames the synthetic melodies. As the section unfolds, the synthesis progressively explores pitch regions inaccessible to the acoustic gaita; although its gestures retain a morphological resemblance to those of the first section, the resulting pitches diverge. Despite these differences, the synthesized voice maintains a subtle connection to the earlier material, preserving traces of the gaita's influence while asserting an independent sonic identity.

This process of gradual detachment does not imply a rupture, but rather a reconfiguration of roles within the musical discourse. As the acoustic gaita recedes into a supportive and textural function, the synthesized voice gains increasing prominence, transitioning from a reactive presence to an initiator of musical action. The shift from imitation to autonomy is articulated not only at the level of pitch organization, but also through changes in rhythmic behavior and gestural direction, preparing the ground for a section in which the synthetic instrument assumes full expressive leadership.

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 traditional vocabulary. This moment of emancipation marks the transformation of technology from a medium of reproduction into a creative agent. As the timbral palette expands and rhythmic structures grow more complex, the synthetic instrument takes the lead in shaping the musical discourse. Rather than dominating or replacing the real gaita, however, this digital voice proposes a new mode of listening—one in which the familiar is refracted through

unfamiliar lenses. The resulting "digital dance" thus emerges as a celebration of autonomy and creative reinterpretation.

Figure 19- Beginning of the section *Danza Digital*.



Source: Vásquez Rincón (2024).

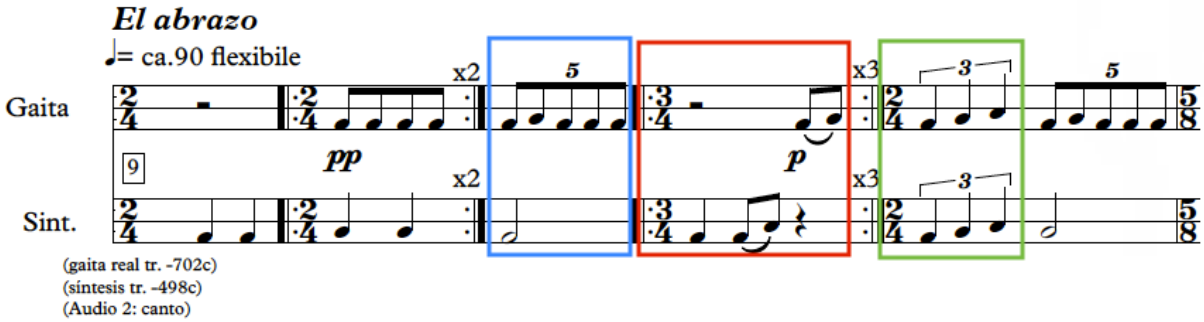
- **E. The Embrace (El abrazo)[16]:**

In the final section, *El abrazo*, the acoustic gaita and the digital synthesis coexist and interact within the same sonic space, sharing the stage with a sense of parity. Both perform similar rhythmic patterns, engaging in a fluid exchange that sustains the rhythmic continuity of the piece. With the activation of bang 9, the real gaita is transposed downward by 702 cents (a perfect fifth +2 cents), while the synthesis is transposed downward by 498 cents (a perfect fourth −2 cents). Simultaneously, a audio layer is introduced, functioning as an additional background texture. As illustrated in Figure 20, the interaction between the two voices unfolds in multiple ways: in the blue frame, each presents distinct gestures; in the red frame, they engage in a question-and-answer dialogue; and in the green frame, they articulate the same gesture in unison. The combination of these varied gestures creates a richly textured auditory experience in which each part complements and enhances the other. Within this shared sonic environment, neither voice assumes dominance. No longer structured by imitation or hierarchy, the acoustic and synthetic gaitas intertwine through rhythmic unison and contrapuntal dialogue, echoing

16 *El abrazo*: https://youtu.be/WoMS1__5Ons?si=8v1rV_r-OGEy577L&t=662

and transforming one another's material. This interplay suggests interdependence—a true musical "embrace," where tradition and technology recognize each other as collaborators in a shared sonic ritual.

Figure 20- Beginning of the section *El abrazo.*



Source: Vásquez Rincón (2024).

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 unfolds as a living process of invention.

Within this framework, the compositional process revealed a particularly compelling dialogue between two conceptions of breath: the "real breath" of the instrumentalist—conditioned by the physical effort and airflow required to produce each gesture on the gaita—and the notion of "infinite breath" made possible through the digital instrument, performed via a MIDI keyboard interface. This contrast between physiological limitation and technological continuity functioned as a productive tension that shaped the musical discourse. Acoustic breath carries the weight of embodiment and effort, while digital breath suggests suspension, extension, and the possibility of sound unconstrained by the body. Together, they redefine breath as a conceptual bridge

between human presence and the sonic possibilities afforded by tecnological tools.

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.

From a compositional perspective, *Entre tanto y tanto, un caminar continuo* emerged through a process grounded an enactive listening (PRADA; ROSSETTI, 2025): listening to the instrument, to the technology, and to the tensions generated by their encounter. Composition unfolded as a field of negotiation in which acoustic behavior, digital abstraction, and embodied gesture continually informed one another. Transformation became the central creative force, guiding decisions across form, timbre, and interaction. The digitally modeled gaita operates as a sonic extension of the acoustic instrument, capable of inhabiting parallel temporalities, pitch regions, and modes of articulation. Through this relationship, the composition explores varying degrees of proximity and distance—imitation, divergence, overlap, and convergence—allowing each section to unfold as a moment within a continuous process of interaction rather than linear development.

The concept of breath plays a structuring role throughout the work, understood simultaneously as a physical condition of sound production and as a poetic device. The finite breath of the instrumentalist and the continuous breath enabled by the digital system generate a productive tension that shapes the musical discourse, giving rise to suspension, accumulation, and release. Breath thus articulates time and effort, linking embodied presence with technological continuity. The compositional process can be understood as a form of walking: attentive, gradual, and situated between inherited musical knowledge and contemporary technological practices. Instead of proposing a fixed outcome, the work sustains an ongoing movement in which tradition and technology remain in dialogue, continually reshaping one another.

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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