

Computational Modeling in Python for the Analysis of Choros: Hybrid Techniques for Pattern Extraction in Brazilian Popular Music.

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Abstract. *This article proposes a hybrid methodology for the computational analysis of the works of Aníbal Augusto Sardinha (Garoto), recognized as one of the most significant figures of instrumental Brazilian choro. The approach integrates symbolic and acoustic analysis procedures utilizing the Python libraries music21 and librosa, enabling automated extraction of structural and expressive parameters from digitized scores and historical recordings. The symbolic corpus is based on the Songbook Choros de Garoto (SESC/IMS), encompassing approximately fifty pieces converted into the MusicXML format. Whenever available, original recordings by Garoto are employed for acoustic analysis, allowing investigation of interpretative aspects such as dynamics, timbre, and tempo. The methodology includes the extraction of tonalities, structural forms, harmonic progressions, melodic n-grams, Mel-frequency cepstral coefficients (MFCCs), chromagrams, and energy curves. Symbolic and acoustic data are integrated into a tabular structure using the pandas library, facilitating exploratory analysis through techniques such as Principal Component Analysis (PCA) and t-Distributed Stochastic Neighbor Embedding (t-SNE). This study represents the initial stage of ongoing doctoral research and aims to contribute to the systematization of computational tools for stylistic studies of Brazilian popular music..*

1. Introduction

In recent decades, advancements in computational tools dedicated to musical analysis have significantly transformed research methodologies in musicology, consolidating an interdisciplinary field that integrates music theory, data science, and signal processing. Computational musicology has enabled innovative approaches in the analysis of diverse repertoires by providing quantitative resources for the systematic examination of melodic, harmonic, formal, and expressive patterns. Internationally, libraries such as music21 and librosa have become reference points for extracting and modeling musical data from symbolic and acoustic sources, respectively.

Despite these advancements, the application of such methodologies to the study of Brazilian repertoires remains incipient. Genres such as choro, which occupy a central role in the development of Brazilian instrumental

language, are still relatively unexplored from a computational perspective. Among its main exponents is Aníbal Augusto Sardinha—known as Garoto—whose works stand out for their harmonic richness, melodic lyricism, and formal inventiveness. Garoto's production offers fertile ground for implementing hybrid computational analyses capable of revealing both compositional structures and expressive nuances in his music.

This paper presents the initial findings of ongoing doctoral research aimed at proposing and validating a hybrid computational methodology for the stylistic analysis of Garoto's oeuvre. By combining symbolic feature extraction from digitized scores in MusicXML format with acoustic analysis of historical recordings, the research seeks to integrate structural and performative data using the Python libraries music21 and librosa. This approach aims not only to characterize recurring stylistic elements of the composer but also to provide a replicable methodology applicable to the study of other Brazilian popular music repertoires.

The following sections outline the theoretical foundations underpinning the proposed model, describe the corpus and materials employed, detail methodological procedures for data extraction and integration, and present preliminary results derived from the analysis of the piece Jorge do Fusa. Finally, the paper discusses perspectives for expanding this methodology to a broader corpus, as well as anticipated developments regarding stylistic analysis and the creation of computational tools tailored to Brazilian music research. The results presented herein can be explored or reproduced using the code available at: [https://github.com/rafayasuda/analise_garoto].

2. Theoretical Framework

Computational music analysis has established itself over recent decades as an interdisciplinary field integrating music theory, data science, and signal processing technologies. At the center of this convergence lies the area of Music Information Retrieval (MIR), responsible for developing methods for extracting, representing, and modeling musical data from sheet music, MIDI files, and audio recordings. As systematized by Müller (2015), these techniques enable integrated approaches to structural analysis, harmonic and melodic pattern

detection, formal segmentation, and expressive characterization of musical performances.

Two Python libraries stand out in the implementation of these methodologies. *music21* (Cuthbert & Ariza, 2010) focuses on symbolic analysis, facilitating the processing of digital scores in formats such as MusicXML. It enables the automated extraction of elements including global and local tonalities, harmonic progressions, melodic patterns through n-grams, and recurrent formal structures. On the other hand, *librosa* (McFee et al., 2015) is widely adopted within MIR for audio analysis, offering tools to extract spectral descriptors (such as MFCCs and chromagrams), beat tracking, tempo estimation, and energy analysis, thereby capturing expressive nuances of musical performances.

Regarding the aesthetic and stylistic dimensions of the object of study, *choro* is recognized for its harmonic sophistication, formal diversity, and expressive richness. It is an urban Brazilian genre historically associated with live performance and oral tradition. According to Almada (2023), *choro* typically presents standardized formal structures—such as AABA and ABACA—combined with frequent modulations, creative reharmonizations, and contrapuntal writing. The presence of traditional cadential formulas with subtle variations underscores the necessity for analytical approaches sensitive to the compositional complexity of the genre.

Authors such as Sandroni (2001) and Livingston-Isenhour and Garcia (2005) characterize *choro* as a hybrid genre, situated between popular and erudite traditions, and between notation and improvisation. These aesthetic and performative dimensions are even more prominent in the work of Aníbal Augusto Sardinha (Garoto), whose musical language is marked by sophisticated melodic lyricism, elaborate harmonies, and structural inventiveness.

In view of this context, the present research proposes a hybrid analytical methodology aiming to integrate symbolic data extracted from scores with acoustic data derived from historical recordings. By combining contemporary computational tools with theoretical references from Brazilian musicological tradition, this approach seeks not only to characterize stylistic traits in Garoto's oeuvre but also to provide a replicable model for the computational analysis of repertoires in Brazilian popular music.

3. Corpus and Materials

The construction of a musical corpus is a fundamental methodological step in computational musicology research. As emphasized by Krumhansl (2000), the term "corpus" refers to an organized collection of musical works selected according to specific criteria, enabling systematic analyses and the generalization of stylistic,

formal, or performative patterns. Within the Brazilian context, Loureiro (2003) underscores that corpus curation should consider both historical representativeness and aesthetic diversity, ensuring that analyzed data reflect core aspects of the studied musical practice.

In this study, a hybrid corpus composed of complementary symbolic and acoustic sources was adopted. The symbolic corpus was based on the *Songbook Choros de Garoto*, published by SESC in partnership with the Instituto Moreira Salles (IMS), comprising approximately fifty works by composer Aníbal Augusto Sardinha—Garoto. The scores were digitized and converted into the MusicXML format, compatible with the *music21* library. This conversion facilitates the automated extraction of musical information, including tonality, harmonic progressions, melodic patterns, and formal structures. The curation process prioritized pieces featuring complete notation, including indications of dynamics, articulation, and meter, thus ensuring greater fidelity in symbolic analysis.

The acoustic corpus, meanwhile, consists of historical recordings by Garoto himself, sourced from remastered compilations and publicly available digital archives. To guarantee analytical quality, audio files were converted to WAV format, with a sampling rate of 44.1 kHz and a 16-bit depth. Track selection was guided by criteria concerning sound quality and interpretative authenticity, prioritizing recordings with clear timbral qualities, minimal noise interference, and well-captured solo instruments.

Correspondence between scores and audio recordings was carefully verified to ensure the integrity of cross-domain analyses between symbolic and acoustic data. This involved detailed comparisons of formal structures and melodic sequences, confirming that the same version of each piece was analyzed across both formats. Such validation is particularly crucial in orally transmitted repertoires like *choro*, where multiple versions of a single piece often coexist.

The adoption of this hybrid corpus aims to simultaneously capture compositional elements encoded within scores and expressive nuances evident in recorded interpretations. This duality enables a comprehensive analysis of Garoto's musical language, integrating notation and performance within a unified perspective.

4. Methodology

The methodology proposed in this study is based on a hybrid computational approach structured into three primary stages: symbolic analysis from digitized scores, acoustic analysis of historical recordings, and integration of data into a unified framework. The central objective is to explore the relationships between compositional elements encoded in musical notation and expressive nuances captured in recorded interpretations through tools specifically suited for each domain. The Python libraries *music21* (Cuthbert & Ariza, 2010) and *librosa* (McFee et al., 2015) were selected as operational bases

for the process.

4.1 Symbolic Analysis with music21

Symbolic analysis will be performed using MusicXML files derived from the scores contained in the Songbook Choros de Garoto. These files will be processed using the music21 library, enabling automated extraction of various musical characteristics relevant to the structural and stylistic comprehension of the works.

The following information will be extracted:

- **Global and Sectional Tonality:** Predominant key signatures and modulation points will be identified using tonal analysis algorithms that segment the compositions into harmonic regions.
- **Harmonic Progressions:** Automated chord labeling will generate representative harmonic sequences, facilitating analysis of recurrence and functional variation.
- **Melodic Patterns:** Melodic n-gram techniques will be applied to detect recurring motifs and thematic transformations, allowing inferences about Garoto's melodic vocabulary.
- **Formal Segmentation:** Based on harmonic and melodic patterns, typical formal structures in choro, such as AABA and ABACA, will be proposed, aligned with specialized literature (Almada,2023).

The extracted symbolic information will be organized into structured tables using the pandas library, facilitating graphical visualization and subsequent statistical analyses.

4.2 Acoustic Analysis with librosa

The acoustic analysis focuses on the extraction of sound descriptors from Garoto's original recordings. Using the librosa library, standardized WAV files were processed in order to capture expressive characteristics of the performances.

The extracted descriptors include:

- **Chromagrams and MFCCs:** Chromagrams are used to identify the spectral distribution of pitch classes, while Mel-Frequency Cepstral Coefficients (MFCCs) serve as indicators of timbral variation throughout the performance.
- **Beat Tracking and Tempo Analysis:** The beat tracking algorithm identifies the average tempo (BPM) and local fluctuations, offering insights into the rhythmic elasticity and expressive timing of the interpretation.
- **Energy Curves (RMS):** Root Mean Square (RMS) energy values are used to map performance dynamics, allowing the

observation of emphasis patterns, contrasts, and expressive variations over time.

These acoustic parameters were automatically extracted, normalized, and exported in CSV format to facilitate integration with symbolic data.

4.3 Data Integration

The final stage of the methodology consists of integrating the data extracted from both symbolic and acoustic domains into a unified tabular structure, enabling cross-analysis of compositional and performative aspects. For this purpose, the pandas library is employed, allowing efficient organization of heterogeneous data within a single analytical matrix.

Each work in the corpus is represented by a row in the table, with columns describing symbolic parameters—such as main key, number of modulations, formal structure, and harmonic progressions—and acoustic parameters—such as average Mel-frequency cepstral coefficients (MFCCs), estimated tempo (BPM), number of detected beats, and dynamic energy statistics (RMS).

This unified database serves as a foundation for visual and exploratory statistical analyses. In later stages of the research, as the doctoral dissertation progresses and the analysis of the complete set of selected works is consolidated, machine learning techniques such as Principal Component Analysis (PCA) and t-Distributed Stochastic Neighbor Embedding (t-SNE) will be applied. These techniques aim to detect stylistic clusters, interpretative trends, and latent structural regularities within the corpus.

The presentation of preliminary results obtained from this integrated model will be detailed in the next section, based on its application to the piece Jorge do Fusa.

5. Preliminary Results

As an initial stage of methodological validation, the hybrid approach was applied to the piece Jorge do Fusa, composed by Aníbal Augusto Sardinha (Garoto). This piece was selected due to the availability of a fully notated score and a high-quality original recording—conditions that are ideal for the integrated application of the music21 and librosa libraries.

5.1 Symbolic Analysis

The global key identified was D major, with modulations to F# minor, A major, E minor, and D minor, as detected through automated tonal segmentation. The formal structure corresponded to an AABA pattern, a recurring format within the choro repertoire (Almada, 2023).

Harmonic progressions, extracted through automatic chord labeling via music21, revealed a predominance of traditional functional harmonies (I, IV, V7), enriched by modal and chromatic resources such as secondary dominants and expressive use of the minor mode.

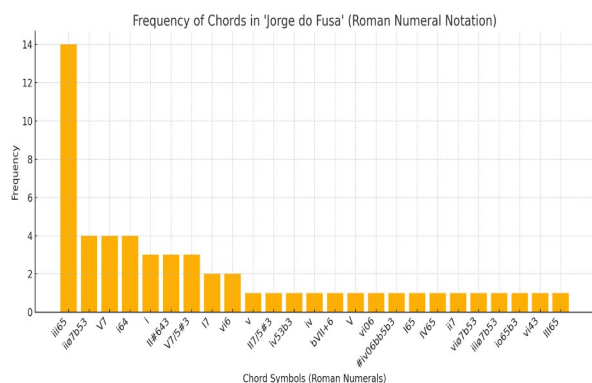


Figure 1: Frequency of Chord

In the melodic domain, n-gram analysis revealed patterns involving non-trivial melodic leaps—such as major ninths, perfect fourths, and augmented seconds—indicating a sophisticated and expressive melodic vocabulary.

5.2 Acoustic Analysis

In the acoustic dimension, the application of the *librosa* library enabled the identification of timbral stability through the regularity of Mel-Frequency Cepstral Coefficients (MFCCs). The average tempo was estimated at 129.2 BPM, with local fluctuations captured by the beat-tracking algorithm, reflecting the rhythmic expressivity of the performance. The chromagram revealed tonal consistency in the execution and the presence of well-defined tonal centers throughout the sections. Finally, the Root-Mean-Square (RMS) energy curve highlighted dynamic patterns, with alternations between moments of intensity and repose that align closely with the formal structure.

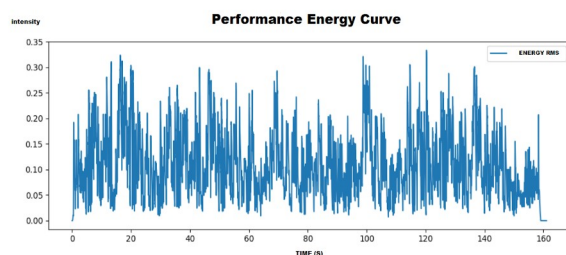


Figure 2: Energy Curve (RMS)

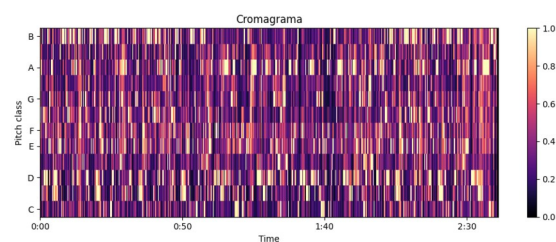


Figure 3: Chromagram of Jorge do Fusa

The Mel-Frequency Cepstral Coefficients (MFCCs) of the performance of *Jorge do Fusa* reveal a moderate timbral variation throughout the recording, consistent with the instrumental stability of a solo interpretation. The analysis shows regular oscillations, suggesting subtle changes in articulation and expressive emphasis across phrases, without drastic spectral shifts. This reinforces the interpretive control characteristic of Garoto's musical language.

5.3 Integration of Results

Symbolic and acoustic data were integrated into a tabular structure using the pandas library. This organization enabled the correlation of dynamic and timbral variations with formal changes, such as the progressive intensification of energy in the A sections and its attenuation in section B.

Symbolic Feature	Acoustic Feature	Value
Symbolic Feature 1	Acoustic Feature 1	0.1234
Symbolic Feature 2	Acoustic Feature 2	0.5678
Symbolic Feature 3	Acoustic Feature 3	0.9012
Symbolic Feature 4	Acoustic Feature 4	0.3456
Symbolic Feature 5	Acoustic Feature 5	0.7890
Symbolic Feature 6	Acoustic Feature 6	0.2345
Symbolic Feature 7	Acoustic Feature 7	0.6789
Symbolic Feature 8	Acoustic Feature 8	0.0123
Symbolic Feature 9	Acoustic Feature 9	0.4567
Symbolic Feature 10	Acoustic Feature 10	0.8901

Work	Main	Structural	No. of	Avg.
	Key	Form	Modulations	MFCC
<i>Jorge do Fusa</i>	<i>D Major</i>	<i>AABA</i>	<i>4</i>	<i>32.2</i>
Estimated	Number of	Avg. RMS	RMS Std.	
Tempo (BPM)	Beats	Energy	Deviation	
<i>129.199</i>	<i>Detected</i>	<i>341</i>	<i>0.11287369</i>	<i>0.06407993</i>

The table presents a summary of the main symbolic and acoustic descriptors extracted from the piece *Jorge do Fusa*. The predominant key was D major, with an AABA formal structure and the occurrence of four modulations. In the acoustic domain, the average MFCC was 32.2, indicating timbral stability; the estimated tempo was approximately 129 BPM, with 341 beats detected. The average RMS energy (0.1129) and its standard deviation (0.0641) suggest expressive variation in dynamics throughout the performance, consistent with the interpretive fluidity characteristic of Garoto's style.

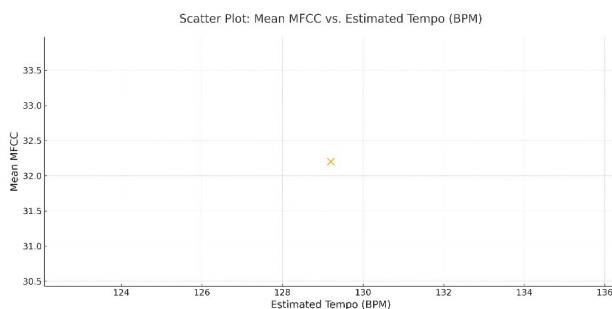


Figure 4: Mean MFCC Vs. Time Estimated

Each point represents a measurement taken throughout the performance of the piece *Jorge do Fusa*. The multiplicity of points reflects local variations in timbre (MFCC) and tempo (BPM) during the performance, which is expected in a frame-based analysis.

6. Final Remarks and Future Perspectives

The hybrid approach developed in this study proved to be promising for the computational analysis of the works of Anibal Augusto Sardinha (Garoto), as it enabled the integration of symbolic parameters — derived from musical notation — and acoustic descriptors extracted from historical recordings. The combined use of the music21 and librosa libraries, together with the data organization via pandas, allowed the construction of a unified tabular structure suitable for visualizations, comparisons, and interpretive correlations between composition and performance.

Although the preliminary results, based on the analysis of the piece *Jorge do Fusa*, highlight the potential of the methodology, it is important to acknowledge the limitations of the current research stage. Fully automating symbolic analysis still presents challenges, especially in accurately identifying formal structures in works with ambiguous or incomplete notation. Likewise, the extraction of acoustic descriptors is sensitive to the quality of the recordings and to the presence of noise or non-musical fluctuations. These constraints reinforce the need for ongoing validation of the applied algorithms, as well as manual and musicologically informed interventions in specific cases.

The next phases of the research will expand the analytical scope to the complete Songbook Choros de Garoto corpus. Additionally, the implementation of interactive visualization interfaces — such as dynamic dashboards — is planned to support exploratory data analysis by researchers, performers, and scholars of Brazilian popular music. In the medium term, the integration of machine learning algorithms is also envisioned, aiming to perform stylistic clustering, detect recurrent harmonic or melodic patterns, and enable the automated classification of musical forms.

This perspective indicates a broadening of the research's reach, potentially leading to the development of a computational ontology of choro. Such an ontology, structured from quantitative descriptors and musical concepts, would not only support stylistic analysis of Garoto's music, but also enable comparisons with other composers of the genre and systematize the formal traits of the Brazilian instrumental repertoire.

Finally, this work emphasizes the importance of its interdisciplinary nature, bringing together expertise from the fields of music, data science, and signal processing to address musicological questions in innovative ways. This investigation represents an initial step in a broader doctoral project, aiming to contribute both to computational musicology and to the study of choro as a valuable aspect of Brazilian musical heritage.

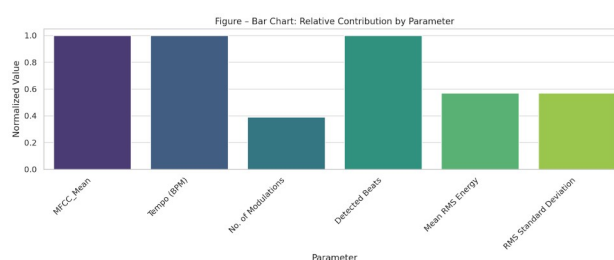


Figure 5 : Graphical Conclusion with Visual Summary of Integrated Analyses

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