# Computational ethnomusicology: a music information retrieval perspective

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## ABSTRACT

Computational ethnomusicology (CE) refers to the use of computational techniques for the study of musics from around the world. It has been a growing field that has benefited from the the many advances that have been made in music information retrieval (MIR). The historical development of CE and the types of tasks that have been addressed so far, is traced in this paper. The use of computational techniques enables types of analysis and processing that would be either impossible or very hard to perform using only audio recordings and human listening. The small but growing subset of music cultures that have been investigated is also overviewed. Research in computational ethnomusicology is still at early stage and the engagement of musicologists and musicians is still limited. The paper ends with interesting directions for future work and suggestions for how to engange musicologists and musicians. The material presented formed the basis of an invited talk by the author presented at the 2014 joint International Computer Music/Sound and Music Computing conference in Athens, Greece, 2014.

## 1. INTRODUCTION

The term *computational ethnomusicology* CE was originally introduced to refer to the design, development and usage of computer tools that have the potential to assist in ethnomusicological research in 2007 [1]. Of course the use of computers for the analysis of world musics predates 2007 but it was mostly after that year that techniques developed in the field of music information retrieval [] were leveraged for this purpose. Even the term CE itself was used much earlier to describe work in analyzing hungarian melodies using computational techniques [].

John Blacking said The main task of ethnomusicology is to explain music and music making with reference to the social, but in terms of the musical factors involved in performance and appreciation (1979:10). For this reason, research in ethnomusicology has, from the beginning, involved analysis of sound, mostly in the form of transcriptions done by ear by trained scholars. Bartks many transcriptions of folk music from his native Hungary are one of the most well known examples. The new technological ability to record music was critical in this process.

Original composed and notated scores and notated transcriptions of music form the basis of a large amount of existing research in musicology. They are representations that capture to a large extent invariant features of music, and they allow the underlying music to be decomposed, slowed down, repeated and abstracted. Until recently recordings did not offer the same flexibility as they mostly could only be heard from beginning to end. Computational techniques have opened new possibilities in the analysis of audio recordings in many cases allowing the same flexibility offered by abstract score representations while still offering a direct connection to the underlying audio signal. We will see later several examples of how such computational tools can be used in computational ethnomusicology research.

Music is not only what notes are played but also about how they are played. Until recently the study of playing technique and live music performance could only be done through human observation. Today it is possible to use sensors (both indirect such as cameras and microphones , and direct such as force sensing resistors) to capture detailed information about the gestures used by musicians on their instruments. Mechanical systems with actuators can also be used to recreate performances that can be acoustically indistinguishable from the original performance. This ability to deconstruct performances through analysis and reconstruct them through synthesis also opens up interesting possibilities in ethnomusicology.

## 2. HISTORICAL DEVELOPMENT

The use of computers in music can be traced to the pioneering work in sound synthesis and music generation conducted in the 1950's at the Bell Laboratories. During the same decade, musicologist and researcher Charles Seager pioneered the use of electronic means for the analysis and transcription of orally transmitted music. The Seeger Melograph was one of the earliest attempts to create a graphical representation of sound for musical research [] and his pioneering vision is now, fifty years later, being realized and expended with work in the field of Computational Ethnomusicology.

The central challenge that research in the emerging field of music information retrieval (MIR) tries to address is how to organize and analyze the vast amounts of music and music-related information available digitally. In addition, it also involves the development of effective tools for listeners, musicians and musicologists that are informed by the results of this computer supported analysis and organization. MIR is an inherently interdisciplinary field combining ideas from many fields including Computer Science, Electrical Engineering, Library and Information Science, Music, and Psychology. The field has a history of approximately 15 years so it is a relatively new research area. Enabling anyone with access to a computer and the Internet to listen to essentially most of recorded music in human history is a remarkable technological achievement that would probably be considered impossible even as recently as 20 years ago. The research area of Music Information Retrieval (MIR) gradually emerged during this time period in order to address the challenge of effectively accessing and interacting with these vast digital collections of music and associated information such as meta-data, reviews, blogs, rankings, and usage/download patterns. There are a few good overview articles for MIR that can serve as entry points to the literature in this field [2, 3, 4].

The main focus of MIR research has been either modern popular music or classical music. The need to consider the large diversity of music cultures from around the world was identified in [5] and an influential position paper that introduced the term Computational ethnomusicology was published in 2007 [1]. Since then there is an increasing amount of research activity in this area that will be surveyed later in this paper. Instrumental to the growth in CE was the award of a Europen Research Council grant for CompMusic, a research project coordinated by Xavier Serra from the Music Technology Group of the Universitat Pompeu Fabra in Barcelona (Spain) [6] from 2011 to 2016. The aim of the project is to advance the automatic description of music by emphasizing cultural specificity. It carries research within the field of music information processing with a domain knowledge approach. The project focuses on five music traditions of the world: Hindustani (North India), Carnatic (South India), Turkish-makam (Turkey), Arab-Andalusian (Maghreb), and Beijing Opera (China). In the next two sections existing work in CE is overviewed using two organization principles: tasks i.e the type of information that the researchers are trying to extract, and cultures. The paper concludes with some future directions and challenges.

## 3. TASKS

The use of computational analysis tools opens up many possiblities for investigating interesting problems and open questions in musicology. Such an investigation can be viewed as a process of information extraction from the music. In this section various types of information that can be extracted automatically from audio signals are described and pointers to the relevant CE literature are provided. This is by no means a comprehensive list of existing work but hopefully it spans enough work to give a good picture of where the field is today.

In many music cultures the continuous dimension of pitch is discretized to a set of fixed discrete values. This division can be enforced mechanically as in the addition of frets in a stringed instrument or can be a matter of convention and practice as is the case in "continuous" instruments such as the trombone or the violin. Tuning systems consist of specific conventions, theories, and rules for how to perform this discretization process. Empirical investigation of tuning systems in actual music performances is a challenging task. For example it is difficult to separate intentional variations in pitch such as vibrato from systematic changes such as playing out of tune. Even a simple question as what tuning is employed in a particular recording is a very difficult problem to solve without computer assistance. Therefore, it should not come as a surprise that probably the CE task that has been investigated the most is tuning/pitch analysis. *Tarsos*' is a software tool for exploring tuning and pitch scales in both non-western and western music [7]. Several music cultures such as classic Ottoman, Hindustani (North Indian) and Carnatic (Sound Indian) music are known to utilize intervals that are smaller than the semitone (the smallest interval in Western music). Theorists have proposed tunining systems in which the octave is subdivided into more than 12 intervals but there is debate about whether some of these smaller subdivisions should be considered ornaments and deviations or where they should be considered part of the scale. Computational approaches can bring more empirical evidence to answer some of these debates in ethnomusicology. Turkish makam music has a long history and a variety of theories and associated notation systems have been proposed to describe it. Through the use of pitch histograms [8] it is possible to empirically investigate these theories and assess how well they correspond to actual practice [9]. Computer-based intonation analysis has also been performed for both vocal Carnatic music [10, 11] and Hindustani music [10].

Other tasks that are based on automatic extraction of the pitch contour followed by some analysis inlcude tonic detection [12], identification of melodic motifs [13], and the investigation of melodic contour stability in the context of religious recitation [14]. Figure 1 shows a web-based interface that enables paradigmatic analysis of melodic contours for investigating melodic stability and its relation to cantillation marks in Jewish Torah Trope recitation. In most cases the foundation of pitch analysis is the extraction of the pitch contour using some fundamental frequency estimation technique (for example a popular one is YIN [15]) and the creation of a pitch histogram frequently utilizing kernel density estimation to create a smoother looking histogram. Raag recognition is another cultural specific topic that is based on pitch analysis followed by classification methods [16, 17].

Another aspect of music that has been investigated in computational ethnomusicology is rhythm, the hierarchical organization of music in time. Rhythm is essential in many music cultures and sometimes plays a much more significant role than in Western classical music. Therefore rhythmic similarity it can form the basis of music recommendation systems for various music cultures. For example the use of rhythmic similarity for Greek and African music has been investigated [18] as well as for Turkish

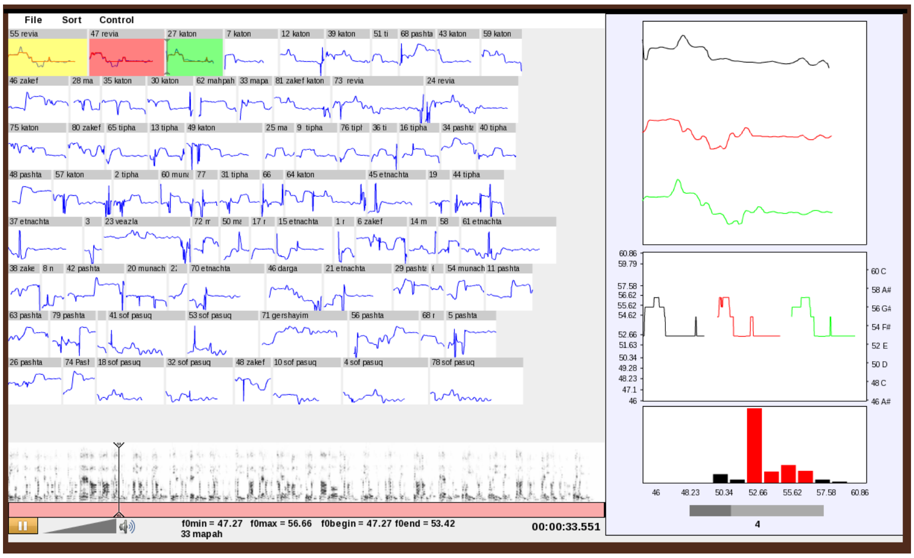


**Figure 1**. Web-based visualization interface which allows users to listen to audio, see pitch contour visualization of different signs, and to enable interactive similarity-based querying.

music [19]. More recently the topic of automatic rhythmic analysis was investigated in the context of Turkish and Indian art music [20]. Typically the results of automatically extracted rhythmic similarity are evaluated using genre information making the assumption that a particular genre of music shares similar rhythmic characteristics. This relation between rhythmic analysis and genre has been thoroughly investigated in a recent cross-disciplinary study [21]. Another type of analysis is the automatic extraction and representation of characteristic rhythmic patterns that has been used to form the basis of a genre classification for Latin Music [22] and in flamenco music [23]. One interesting possibility in CE is the utilization of culture specific information to perform music information retrieval tasks that would otherwise be too hard to compute using general methods. For example a lot of Afro-Cuban is structured around a repated rhythmic pattern called the clave. Even though this style of music has very complex rhythms and big tempo variations it has been shown that using the underlying clave it is possible to perform accurate beat tracking using a rotation-aware clave template matching and dynamic programming [24]. The designed method is specific to this type of music and not as general as existing beat tracking methods which can not handle the rhythmic complexity of this particular type of music.

Beat tracking can be used to investigate the fascinating issue of micro-timing i.e the study of systematic timing deviations from what is considered the canonical theoretical model of a rhythm. Figure 2 shows an example of micro-timing analysis based on automatic analysis of Afro-cuban music [24]. It utilizes a visualization in which the time-varying sequences of onsets corresponding to the clave are visually made to start at the same "downbeat" and the stretched to have equal length (the tempo curve is shown on the right of the figure). That way it is possible to visualize systematic timing deviations such as playing behind the beat in the last pulse of the clave (notice the onsets being mostly on the right of the theoretical blue line in Figure 2) without being affected by the tempo changes (notice the tempo curve ranges from 150 beats-per-minute (BPM) to 110 (BPM)).

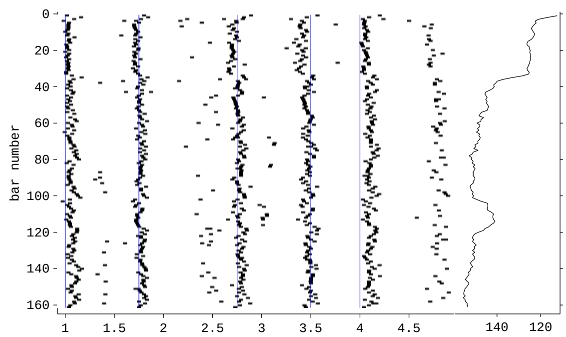


**Figure 2**. Bar-wrapping visualization

Pitch and rhythm analyzed can be viewed as specialized cases of the more general problem of music transcription which is the derivation of an abstract symbolic representation of the music i.e a musical score that can be used for analysis and performance [25]. Music transcription is a really hard problem in the general case but specific variants can be solved with reasonable accuracy. A related problem is the linking of scores to audio recordings which is somewhat easier [26]. When the music is mostly monophonic and has specific characteristics it is possible to apply techniques for predominant melody separation [27] in order to perform more accurate transcriptions [28]. Tabla transcription (an Indian percussion instrument has also been investigating [29, 30].

In addition to these more specific tasks one can envision more general MIR systems that can be used to more effectively access ethnic music from around the world [31]. The existing lumping of everything that is not Western music as

World Music is hardly useful for accessing ethnic music. An obvious way to structure such as an interface is around geographic location of origin [32]. At a more abstract level digital libraries can be used to support representations and annotations for ethnomusicological research [33]. Visualization techniques such as self-organizing maps have also been used as ways to explore collections of folk songs and their corresponding similarities [34]. Dunya is a web-based interface that utilizes many modern techniques from music information retrieval for browing large collections of world music [35].

## 4. CULTURES

All human cultures that we know of have developed some form of music. Therefore there is a staggering diversity of music cultures around the world many of which are in danger of becoming extinct. Over the last couple of years research in computational ethnomusicology has been steadily encompassing more cultures. In this section existing CE work is organized according to the culture of study rather than the tasks that were used in the previous section. The order is roughly alphabetical and the list is definitely not exhaustive but gives a sense of current coverage. The creation of a research corpora is an important first step in CE research. African music has incredible diversity that mirrors its cultural and linguistic diversity. It has been the topic of works in CE especially related to rhythm [18, 36] and ptich [37]. The transcription of aboriginal australian music has been investigated [38]. Rhythm analysis and microtiming visualization has been explored in the context of Afro-Cuban music [24]. A corpus of Jingju (Being Opera) music has been created to support melodic analysis [39]. Carnatic music comes from the south of India and has been explored in tasks such as intonation analysis [10, 11] and tonic identification [12]. Flamenco music has also been investigated in the context of pitch analysis and transcription [27]. Greek music contains uneven rhythms and has been investigated in the context of rhythmic similarity [18]. Makam music and classical Ottoman music have been studied mostly for intonation [40, 41] but also for linking scores to audio recordings [26]. The intonation of hindustani music has also been explored [10] as well as rhythmic transcription [29, 30]. A web-based tool for paradigmatic analysis to study melodic stability and variation in Jewish Torah trope recitation has been developed [14].

## 5. FUTURE DIRECTIONS AND CHALLENGES

The filed of computational ethnomusicology is still in its infancy and most of existing work is exploratory. As the field matures it can play an increasing role in addressing long standing musicological questions. This will require more active involvement of musicologists who can formulate hypotheses that can then be tested empirically through computational analysis. The majority of existing work in CE (and MIR for that matter) is centered around processing collections of audio recordings. An audio recording consists of the mixture of a number of individual instruments which make analysis and transcription challenging. By recording each sound individually it is easier to understand the interactions between musicians in complicated improvised music such as Indonesian gamelan or African polyphonic music [42]. Even the audio recording of a single instrument does not reveal all the complexity of the gestures used to create the music. For example the strumming pattern in guitar playing is not easily extracted from audio and neither is the usage pattern of left and right hand playing in drums.

**Figure 3**. Top left: Gyil on top of vibraphone for showing scale, Top right: piezo sensors under bars, Bottom Left: 2882 input, Bottom Right: overview

Hyperinstruments are acoustic instruments that have been augmented with sensing hardware to capture performance information. The majority of existing hyperinstruments have been standard western instruments such as guitars, keyboards, piano and strings. In world music, the use of hyper-instruments has been explored in the context of North Indian music [43] and digital sensors have been used in the development of Gamelan Electrica [44], a new electronic set of instruments based on Balinese performance practice. One interesting motivation behind the design of Gamelan Electrica is a reduction in physical size and weight, simplifying transportation. This concern also motivated a system for direct, indirect and surrogate sensing [45] for the African Gyil xylophone [46].

The data collected through such sensing systems can be used to study the nuances of performace and potentially offer new musicological insights. As an example such data has been used as the basis of perfomer identification [47].

Finally an interesting future, and not explored explored, direction for the field of CE is to assist with music pedagogy. Unlike western instruments for which there is a plethora of resources and teachers many traditional instruments are under threat of extinction and the number of expert musicians who can play them is dwindling. Music analysis tools can be used to provide feedback to musicians such as information about intonation [] and to give insights about playing techniques.

In summary, computational ethnomusicology is a growing research area that is leveraging the techniques developed in music information retrieval.

In the last few years there is a variety of tasks that have been explored and applied to a variety of music cultures in many cases using culture specific knowledge. There are several challlenges that CE researchers still face. These include the limited involvement of musicologists, the lack of large standardized collections, and the involvement of export musicians and performers. Most existing CE work is exploratory but there is a enormous potential for future work both continuing existing threads of inquiry and expanding into other areas such as sensor and actuator based performance analysis and music pedagogy.

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## 6. REFERENCES

[1] G. Tzanetakis, A. Kapur, W. A. Schloss, and M. Wright, "Computational ethnomusicology," *Journal of interdisciplinary music studies*, vol. 1, no. 2, pp. 1–24, 2007.

[2] N. Orio, *Music retrieval: A tutorial and review*. now publishers Inc, 2006.

[3] M. A. Casey, R. Veltkamp, M. Goto, M. Leman, C. Rhodes, and M. Slaney, "Content-based music information retrieval: Current directions and future challenges," *Proceedings of the IEEE*, vol. 96, no. 4, pp. 668–696, 2008.

[4] T. Li, M. Ogihara, and G. Tzanetakis, *Music data mining*. CRC Press, 2011.

[5] J. Futrelle and J. S. Downie, "Interdisciplinary communities and research issues in music information retrieval." in *ISMIR*, vol. 2, 2002, pp. 215–221.

[6] X. Serra, "A multicultural approach in music information research." in *ISMIR*, 2011, pp. 151–156.

[7] J. Six and O. Cornelis, "Tarsos: a platform to explore pitch scales in non-western and western music," in *12th International Society for Music Information Retrieval Conference (ISMIR-2011)*. University of Miami, Frost School of Music, 2011, pp. 169–174.

[8] G. Tzanetakis, A. Ermolinskyi, and P. Cook, "Pitch histograms in audio and symbolic music information retrieval," *Journal of New Music Research*, vol. 32, no. 2, pp. 143–152, 2003.

[9] B. Bozkurt, O. Yarman, M. K. Karaosmanoğlu, and C. Akkoç, "Weighing diverse theoretical models on turkish maqam music against pitch measurements: A comparison of peaks automatically derived from frequency histograms with proposed scale tones," *Journal of New Music Research*, vol. 38, no. 1, pp. 45–70, 2009.

[10] J. Serra, G. K. Koduri, M. Miron, and X. Serra, "Assessing the tuning of sung indian classical music." in *ISMIR*, 2011, pp. 157–162.

[11] G. K. Koduri, J. Serra, and X. Serra, "Characterization of intonation in carnatic music by parametrizing pitch histograms," in *Proc. ISMIR*. Citeseer, 2012.

[12] J. Salamon, S. Gulati, and X. Serra, "A multipitch approach to tonic identification in indian classical music." in *ISMIR*, 2012, pp. 499–504.

[13] J. C. Ross, T. Vinutha, and P. Rao, "Detecting melodic motifs from audio for hindustani classical music." in *ISMIR*, 2012, pp. 193–198.

[14] P. Kranenburg, D. P. Biró, S. R. Ness, and G. Tzanetakis, "A computational investigation of melodic contour stability in jewish torah trope performance traditions," in *Proceedings of the International Society on Music Information Retrieval (ISMIR2011) Conference*, 2011.

[15] A. De Cheveigné and H. Kawahara, "Yin, a fundamental frequency estimator for speech and music," *The Journal of the Acoustical Society of America*, vol. 111, no. 4, pp. 1917–1930, 2002.

[16] P. Chordia and A. Rae, "Raag recognition using pitch-class and pitch-class dyad distributions." in *ISMIR*. Citeseer, 2007, pp. 431–436.

[17] G. K. Koduri, S. Gulati, P. Rao, and X. Serra, "Rāga recognition based on pitch distribution methods," *Journal of New Music Research*, vol. 41, no. 4, pp. 337–350, 2012.

[18] I. Antonopoulos, A. Pikrakis, S. Theodoridis, O. Cornelis, D. Moelants, and M. Leman, "Music retrieval by rhythmic similarity applied on greek and african traditional music," in *Proceedings of the 8th International Conference on Music Information Retrieval*, 2007, pp. 297–300.

[19] A. Holzapfel and Y. Stylianou, "Rhythmic similarity in traditional turkish music." in *ISMIR*, 2009, pp. 99–104.

[20] A. Srinivasamurthy, A. Holzapfel, and X. Serra, "In search of automatic rhythm analysis methods for turkish and indian art music," *Journal of New Music Research*, vol. 43, no. 1, pp. 94–114, 2014.

[21] T. M. Esparza, J. P. Bello, and E. J. Humphrey, "From genre classification to rhythm similarity: Computational and musicological insights," *Journal of New Music Research*, no. ahead-of-print, pp. 1–19, 2014.

[22] T. Völkel, J. Abeßer, C. Dittmar, and H. Großmann, "Automatic genre classification of latin american music using characteristic rhythmic patterns," in *Proceedings of the 5th Audio Mostly Conference: A Conference on Interaction with Sound*. ACM, 2010, p. 16.

[23] C. Guastavino, F. Gomez, G. Toussaint, F. Marandola, and E. Gómez, "Measuring similarity between flamenco rhythmic patterns," *Journal of New Music Research*, vol. 38, no. 2, pp. 129–138, 2009.

[24] M. Wright, W. A. Schloss, and G. Tzanetakis, "Analyzing afro-cuban rhythms using rotation-aware clave template matching with dynamic programming." in *ISMIR*, 2008, pp. 647–652.

[25] A. Klapuri, M. Davy *et al.*, *Signal processing methods for music transcription*. Springer, 2006, vol. 1.

[26] S. Şentürk, A. Holzapfel, and X. Serra, "Linking scores and audio recordings in makam music of turkey," *Journal of New Music Research*, vol. 43, no. 1, pp. 34–52, 2014.

[27] E. Gómez, F. J. Cañadas-Quesada, J. Salamon, J. Bonada, P. V. Candea, and P. C. Molero, "Predominant fundamental frequency estimation vs singing voice separation for the automatic transcription of accompanied flamenco singing." in *ISMIR*, 2012, pp. 601–606.

[28] E. Gómez and J. Bonada, "Towards computer-assisted flamenco transcription: An experimental comparison of automatic transcription algorithms as applied to a cappella singing," *Computer Music Journal*, vol. 37, no. 2, pp. 73–90, 2013.

[29] O. Gillet and G. Richard, "Automatic labelling of tabla signals," in *Proc. of the 4th ISMIR Conf*, 2003.

[30] P. Chordia, "Segmentation and recognition of tabla strokes." in *ISMIR*, vol. 20056, 2005, pp. 107–114.

[31] O. Cornelis, D. Moelants, and M. Leman, "Global access to ethnic music: the next big challenge?" in *10th International Society for Music Information Retrieval Conference (ISMIR-2009)*. International Society for music Information Retrieval, 2009.

[32] M. Magas and P. Proutskova, "A location-tracking interface for ethnomusicological collections," in *Workshop on Exploring Musical Information Spaces*, 2009.

[33] G. Strle and M. Marolt, "The ethnomuse digital library: conceptual representation and annotation of ethnomusicological materials," *International Journal on Digital Libraries*, vol. 12, no. 2-3, pp. 105–119, 2012.

[34] Z. Juhász, "Low dimensional visualization of folk music systems using the self organizing cloud." in *ISMIR*, 2011, pp. 299–304.

[35] A. Porter, M. Sordo, and X. Serra, "Dunya: A system for browsing audio music collections exploiting cultural context," in *Proceedings of 14th International Society for Music Information Retrieval Conference (ISMIR 2013), Curitiba, Brazil*. PPGIa, PUCPR Curitiba, Brazil, 2013, pp. 101–106.

[36] T. Lidy, C. N. Silla Jr, O. Cornelis, F. Gouyon, A. Rauber, C. A. Kaestner, and A. L. Koerich, "On the suitability of state-of-the-art music information retrieval methods for analyzing, categorizing and accessing non-western and ethnic music collections," *Signal Processing*, vol. 90, no. 4, pp. 1032–1048, 2010.

[37] D. Moelants, O. Cornelis, and M. Leman, "Exploring african tone scales," in *10th International Society for Music Information Retrieval Conference (ISMIR-2009)*. International Society for music Information Retrieval, 2009, pp. 489–494.

[38] A. Nesbit, L. Hollenberg, and A. Senyard, "Towards automatic transcription of australian aboriginal music." in *ISMIR*, 2004.

[39] R. C. Repetto and X. Serra, "Creating a corpus of jingju (beijing opera) music and possibilities for melodic analysis," in *15th International Society for Music Information Retrieval Conference*.

[40] B. Bozkurt, "Features for analysis of makam music," in *Serra X, Rao P, Murthy H, Bozkurt B, editors. Proceedings of the 2nd CompMusic Workshop; 2012 Jul 12-13; Istanbul, Turkey. Barcelona: Universitat Pompeu Fabra; 2012. p. 61-65*. Universitat Pompeu Fabra, 2012.

[41] B. Bozkurt, R. Ayangil, and A. Holzapfel, "Computational analysis of turkish makam music: review of state-of-the-art and challenges," *Journal of New Music Research*, vol. 43, no. 1, pp. 3–23, 2014.

[42] S. Arom, M. Thom, B. Tuckett, and R. Boyd, *African polyphony and polyrhythm: musical structure and methodology*. Cambridge university press Cambridge, 1991.

[43] A. Kapur, P. Davidson, P. Cook, P. Driessen, and W. Schloss, "Digitizing north indian performance," in *Proc. of the Int. Computer Music Conf.*, 2004, pp. 556–563.

[44] L. S. Pardue, A. Boch, M. Boch, C. Southworth, and A. Rigopulos, "Gamelan elektrika: An electronic balinese gamelan," in *Proc. Int. Conf. on New Interfaces for Musical Expression (NIME)*, 2011.

[45] A. Tindale, A. Kapur, and G. Tzanetakis, "Training surrogate sensors in musical gesture acquisition systems," *Multimedia, IEEE Transactions on*, vol. 13, no. 1, pp. 50–59, 2011.

[46] S. Trail, T. Fernandes, D. Godlovitch, and G. Tzanetakis, "Direct and surrogate sensing for the gyil african xylophone," in *Proc. Int. Conf. New Interfaces for Musical Expression (NIME)*, 2012.

[47] J. Hochenbaum, A. Kapur, and M. Wright, "Multimodal musician recognition," in *Proceedings of the International Conference on New Interfaces for Musical Expression*, 2010.