Towards Intelligent Orchestration Systems

Aurélien Antoine and Eduardo R. Miranda

Interdisciplinary Centre for Computer Music Research (ICCMR),
University of Plymouth,
Plymouth
PL4 8AA, UK
aurelien.antoine@postgrad.plymouth.ac.uk

Abstract. Orchestration is a problem that has been relatively unexplored in computer music until recently. This is perhaps due to its complexity. This paper presents a survey of the field of computer-assisted orchestration. The span of such survey covers different orchestration systems that were initiated by the spectral music movement and developed during the last 40 years in order to establish the current state-of-the-art. In this paper, we also introduce some of our current work-in-progress ideas, which work towards intelligent orchestration systems.

Keywords: Computer-Aided Orchestration, Orchestration, Intelligent Systems, Computer Music, Spectral Music, Timbre

1 Introduction

This paper focuses on a specific compositional art named orchestration from the perspective of Western classical music. Orchestration can be defined as the art of combining pitches to compose music for an orchestra or more generally an ensemble. This involves writing for a number of instruments and can be seen as a symbolic view of composing. Furthermore, orchestration is the art of mixing instrumental properties. For example, by combining small sounds from different instruments, the orchestration creates a sound that could not exist on its own. This second aspect can be described as the sonic view of composing. Orchestration is an interesting compositional art as it can help achieve a musical idea that cannot be done with a single instrument. Even if some attempts to define the art of orchestration have been done, such as in [7], [19], [20] and [1], its teaching and practice are mainly empirical. This is because there is no mathematical foundation or long theoretical traditions for this activity as there is for other compositional aspects. This is possibly the reason that this musical discipline is said to be "*at the crossing of daring and experience*"[24].

Since the invention of the computer, composers have been interested in exploring its potential in the compositional process. The *Illiac Suite* [16] was one of the first pieces to use computers to compose music. Since, several different computing techniques and systems have been developed for musical composition. These tools mainly allow composers to manipulate musical symbolic objects, such as notes or chords giving them the ability to focus on harmony and rhythm. These aspects of composition have been successfully implemented in several Computer-Aided Composition systems since the late 1950s (see [29], [3] or [26] for examples) . These tools can aid or completely automate the compositional process. In this paper, we use the term computer-assisted system, and not automatic composition system as it includes all kinds of systems that can help the compositional process.

Until recently, orchestration has been relatively unexplored in the domain of computer music. We believe that computers can be helpful in orchestration as they have been and still are for other musical writings. In this paper, we present an overview of the computer-assisted orchestration field, including different systems and examples of compositions. We also introduce our own ideas for future developments in this fascinating field, which work toward intelligent orchestration systems.

2 Computer-Assisted Orchestration

Here we define computer-assisted orchestration (or computer-aided orchestration) as a system that assists users/composers to make a piece for an ensemble or an orchestra. This could result in a generated/automatic orchestration or in helping to orchestrate a part. This will not replace the composer, but assist in the compositional process in many ways.

For the purposes of this paper, we divide computer-aided orchestration systems in two categories: “semi-automated” and “automatic”. We classify semi-automated as a system or a set of techniques that involve using computers in one or several parts of the orchestration process. In these systems, the composition is still dependant on a hand-written process. We define automatic as a system in which the orchestration is completely produced by the computer. However, this does not necessary result in a complete composition, it can be used as a starting point or as inspiration for an orchestration.

2.1 Semi-Automated Systems

The first computer-assisted orchestration systems can be associated with the *Spectral Music* movement initiated in the 1970s. In [11], Hugues Dufourt coined the term spectral music. Composers such as Gérard Grisey and Tristan Murail initiated this movement in France in the early 1970s, with the ensemble *L'Itinéraire*, based at IRCAM in Paris. During the same period, some composers such as Johannes Fritsch or Clarence Barlow, from the Feedback Studio situated in Cologne, were also part of this new musical movement.

One of the first pieces associated with spectral music is entitled *Partiels*, which was composed by Gérard Grisey in 1975 for 18 instruments. The spectrum analysis was realised on the trombone using an electronic sonogram. Following this experiment and the development of the technological and scientific knowledge and tools, various composers started to use computers to help them to compose music for an ensemble.

In his piece *L'Ésprit des dunes* (1994) realised at IRCAM, Tristan Murail started his composition by analysing fragments from different sources, such as diphonic Mongolian singing and Tibetan singing. The material of this composition, for an ensemble of 11 instruments and electronics, was generated by spectral analysis of the aforementioned sources. He used an analysis program developed for additive synthesis, then constructed a database of these analyses to be evaluated and modified with libraries he developed in the visual programming environment PatchWork [3].

Some composers used speech analysis for their compositions. Clarence Barlow developed a technique called *Synthrumentation*, which consisted of doing spectral analysis of speech and then mapping these analyses to acoustic instruments [5] [27]. Claudy Malherbe also used voice analysis techniques for some of his compositions. In *Locus* (1997) [23], a piece for four voices and electronics, Malherbe recorded the singers using two microphones placed at two different distances in order to have two different characteristic recordings. After the segmentation, smoothing and normalisation of the recordings, Malherbe applied a FFT analysis to obtain the representation of these recordings in the form of a sonogram. Then, a detection of partials was applied and the most prominent were selected. These data were subsequently input into PatchWork and transcribed into symbolic representations for ease of manipulation. For the rhythmic representation and manipulation, Malherbe used *Kant*, a rhythmic editor developed at IRCAM by the Computer Assisted Composition group[1].

More recently, for his musical piece entitled *Metal Extensions* (2001), Yann Maresz used a set of techniques combining handwriting and computational processes. In [24], he described his process, as follows:

"Selection of the region of sound to orchestrate from the electronic sound file, placement by hand of markers on the region within the sound file that interested me, for a chord-sequence analysis with AudioSculpt (peaks), inharmonic partial analysis on the totality of the sound file in the same programme, transcription of the given results into symbolic notation in OpenMusic and finally, realization of the final score by hand."

As a summary, several composers began to see the ability of the computer to help them orchestrate musical ideas, or at least using computers in various compositional processes. As seen with the spectral movement, computers were used for spectral analysis and representations of audio signals. Composers used software, such as AudioSculpt, PatchWork or OpenMusic, to analyse sound, and also for the representation and the manipulation of the symbolic view of orchestration.

With the evolution of technology and the experimentations of several composers, the idea of developing systems for orchestration started to arise in some research groups.

[1] http://www.ircam.fr/repmus.html

2.2 Automatic Systems

Surprisingly, there are only a few computer-aided orchestration systems available. The majority of these have been developed in the last decade. This could be due to the complexity of orchestration and the limits of the available technology. However, in this section, we present the attempts of designing computer-assisted orchestration tools we know of so far. One of the first attempts is a tool developed by Rose and Hetrik [30]. They propose a system that analyses a given orchestration. It is also possible to give a target sound to the system and it outputs an orchestration that tries to approach the target file. Their algorithm uses a Singular Value Decomposition (SVD) method either for the analysis of a given orchestration or the proposition of new orchestrations using the spectrum of the target sound. The SVD approach is interesting in terms of low calculation costs and the solution is the nearest to the target sound. However, this approach does not take into account the position of the orchestra and the problem of instrumental combinations.

Psenicka proposes another approach, with his program called *SPORCH* (short for SPectral ORCHestration) [28]. Like the system proposed by Rose and Hetrik, this program analyses a target file and outputs the orchestration solutions in the form of a list of data. This data comprises of instrument names, pitches and dynamic levels in order to create timbre and quality that fit the target file. Psenicka decided to perform the searching algorithm focussing on instruments, instead of doing it on sounds. Hence, the system is divided in two parts: the instruments database and the orchestration function. The database first needs to be built in order to run the program and it contains a list of instruments with pitch range, dynamic level range and the most significant partials associated with instrument (See [28] for more details). To find the orchestration solutions, Psenicka uses an iterative matching algorithm to establish the combination of instruments that fit the original file. The algorithm extracts the peaks of the target sound and then compares them with each instrument in the database in order to select those closest in frequency. This approach has a low computational cost and the instrumental composition of the orchestra is incorporated in the matching algorithm. However, this method tends to output simple orchestrations and only the solution that best matches the target file, and, therefore, it discards all other solutions that could be more interesting in terms of musical ideas.

Another attempt is the system developed by Hummel [17]. Like Psenicka's method, he uses an iterative algorithm, but instead of analysing spectral peaks, the program works with spectral envelopes - the frequency-amplitude derived from a FFT analysis. As with the two previous systems, it analyses a target sound, retrieving its spectral envelope and then searches iteratively for the best approximation. Hummel says his system works better with non-pitched sounds (e.g. whispered vowels). This is due to it using spectral envelopes instead of spectral peaks. Hence, the perception of the pitches resulting from the solutions can be different from the pitches of the target file.

IRCAM addressed the question of computer-assisted orchestration in 2003, initiated by a research project proposed by Yann Maresz [24], whose works are mentioned in the previous section of this paper. This resulted in three Ph.D. theses [35] [8] [13] and computer-aided orchestration programs that evolved through the years. Like the aforementioned systems, the user inputs a target sound and the program computes an orchestration. The first version, named *Orchidée*, was the result of the two Ph.D. theses written by Damien Tardieu [35] and Grégoire Carpentier [8]. They respectively addressed the problem of analysis of instrumental sound and its perception, and the rapid increase of the possible solutions produced by the system. The system extracts some audio descriptors from the target sound, and also from the audio samples contained in the orchestra database. These descriptors are the material for the combinatorial algorithm developed to match the target sounds [36][9]. The algorithm does not output only the best solution but rather a selection optimal solutions, which is an advantage as it proposes different orchestrations for one target sound. This version does not consider temporal problems of orchestration. It proposes only static orchestration solutions and the system works with static and harmonic target sounds. Jonathan Harvey, assisted by researchers and computer music designers from IRCAM, was one of the first composers to benefit from this new computer-assisted orchestration system. He used it for his composition *Speakings* (2008), which is for live electronics and a large orchestra [25]. He recorded three vowels, as mantra sung: *Oh/Ah/Hum*. Then, his idea was to input these recordings into *Orchidée* in order to try to imitate the sound of the sung mantra with an ensemble of 13 instruments.

The system evolved into a new version, under the name *Ato-ms* (for Abstract Temporal Orchestration), and it is the result of the third Ph.D. thesis by Philippe Esling [13]. One of the major improvements of this version is the management of time, which generates orchestration solutions within a time space as opposed to static. Another improvement is the use of a multi-objective and time-series matching algorithm, which creates an optimal warping algorithm. In this version, the user can design envelopes for the audio features thereby creating an abstract target. According to Maresz [24], the solutions "*suffer from a lack of quality in their timbral accuracy*" and the two versions only address the problem of timbre matching.

In November 2014, IRCAM released a complete new version of this system, named *Orchids*[2] (Fig. 1). This standalone application implements the best features from its predecessors and integrates new improvements. It proposes abstract and temporal orchestration and is also optimised for timbral mixture. Like the aforementioned systems, the user inputs a target sound, but in *Orchids* they also have the ability to design an abstract target by shaping various psychoacoustic descriptors. *Orchids* also includes a database of over 30 orchestral instruments, whose samples are analysed and indexed by the program. The user can extend the sound database by simply adding a folder into the program, which the system will analyse and index. The user has the ability to define the instruments they want to include in the orchestra. Moreover, the user can position the instruments, as *Orchids* integrates the notion of spatialisation of the orchestral

[2] Orchids is available at http://www.forumnet.ircam.fr/product/orchids

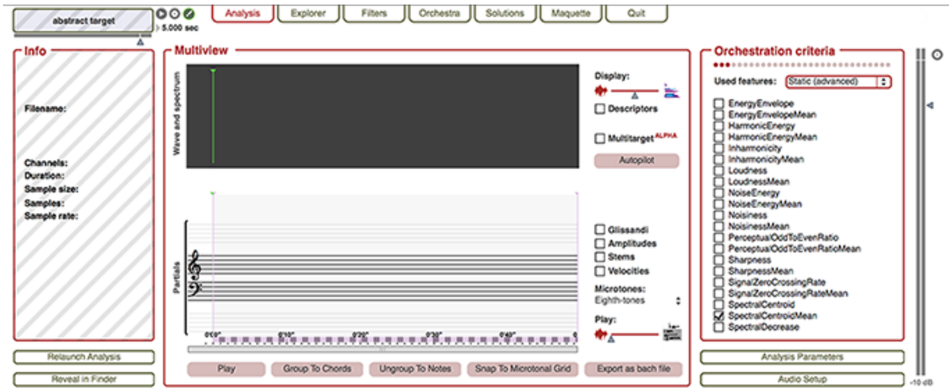

Fig. 1. *Orchids* interface, showing the *Analysis* tab

space. The system first analyses the defined psychoacoustic features of the target. Different matching algorithms are available, specific to the type of solutions the user wants or the more appropriate for the type of the audio file (see [14]). *Orchids* usually proposes several orchestration solutions in the form of a musical score. The program uses the *Bach* library[3] for the symbolic representations. It is also possible to listen to the solutions, thanks to the audio samples contained in the database, before exporting the interesting orchestrations. Furthermore, the user has the ability to start to construct and edit the composition directly inside the program in addition to exporting it afterwards.

In this section, we have discussed three different approaches to try to incorporate the complex problem of orchestration into computer-assisted orchestration systems. The latest program, *Orchids*, presents promising improvements for the problem of computer orchestration and is set to be a powerful tool for computer-aided orchestration. However, a problem we found in these systems is how to classify the solutions or, in other words, how to guide the system to match the kind of orchestration or sound we want. The aforementioned systems usually propose several solutions, and the user can spend a lot time before the 'best' orchestration is found. In the next section of this paper, we discuss solutions of these questions and introduce ideas to improve computer-assisted orchestration systems.

3 Future Developments of Orchestration Systems

As described in the previous section, computer-aided orchestration systems have evolved during the last ten years. In regards to the current state-of-the-art, *Orchids* presents the most efficient and interesting approaches to solving some problems of orchestration. However, *Orchids* produces numerous solutions to orchestrating a given sound, which is tedious and time-consuming to go through.

[3] http://www.bachproject.net

We believe the next step in computer-aided orchestration is to focus on how to personalise systems to a user's style in order to offer more appropriate orchestration solutions. We do not want to completely restrain the solutions, as chance or surprise is part of the compositional process. The ability to have all possible solutions should still be available, but systems could be more efficient in regards to achieving composer specific musical ideas.

Timbre characteristics are important in composing for an orchestra, as it involves writing for instruments that can play simultaneously; thus creating a unique new sound. From this observation, we believe timbre can be a useful method to filter the solutions proposed by a system. This could help the composer to achieve the orchestration they have in mind. In order to discuss this approach, we need to define the notion of timbre, then we introduce our ideas to filter the solutions proposed by a computer-assisted orchestration system.

3.1 Timbre

Working on computer-aided orchestration, we will focus only on instrumental music, therefore in the attempt of defining the term timbre we will omit the timbral characteristics of electroacoustic music. The notion of musical timbre is complex and has been largely discussed in the last decades (see [21] or [34] for examples). However, the American Standards Association [2] suggests the following definition: "*Timbre is that attribute of auditory sensation in terms of which a listener can judge that two sounds similarly presented and having the same loudness and pitch are dissimilar*". Furthermore, a note to the definition adds: "*Timbre depends primarily upon the spectrum of stimulus, but it also depends upon the wave form, the sound pressure, and the frequency location of the spectrum of the stimulus*". To summarise, timbre is all the sound properties that enable us to distinguish and recognise one instrument's sound from an other.

3.2 Filtering Solutions With Timbral Characteristics

As discussed in the previous section, the term timbre is not easily defined. However, the method of using timbre to compose music is a widespread practice [12] [6]. Timbre is also an important notion of the complex process of writing for an orchestra. The instrumental mixture is a fusion of timbres of the individual instrument's sounds. Effects emerging from these fusions are musically interesting and composers often integrate this aspect in their orchestral processes. This notion of instrumental mixtures is incorporated in the matching algorithms used in computer-aided orchestration systems.

Composers are not necessarily acousticians and the psychoacoustics proprieties used in computer-aided orchestration systems are not always explicit. Hence, it is not very intuitive for composers to use these parameters to define the type of solutions they want. From this observation, we decided to use the timbre space to propose a method to filter orchestration solutions. Composers may be looking for specific perceptions of the timbres emerging from their instrumental mixtures, to achieve their musical ideas. We propose to offer the user the possibility to choose the type of solutions, according to verbal descriptors of timbral qualities.

Terms like brightness or roughness are words from the everyday language used to describe timbre and its perception. These terms are more explicit than their correlated acoustic features (e.g. spectral centroid, critical bands, etc). In his Ph.D. thesis, Duncan Williams made a list of different timbral attributes, with their associated acoustic cues [40], which we decided to use as initial timbral attributes to look at and implement into our method.

We decided to use the most advanced computer-aided orchestration system so far: *Orchids*. This system proposes several interesting orchestration solutions, but we think too many solutions can sometimes be unproductive, as the user would spend a considerable amount of time listening to them before finding the 'perfect' one. This is one of the reasons why we propose to design a new approach to classify the solutions using timbral attributes. We are aware that perception of sound could vary from each person. So, we decided to use the available literature for each timbral quality as a starting reference for our system. Our algorithm uses solutions generated by Orchids as its input. The first step is to analyse all the generated solutions. Then, we use the literature about each timbral attribute to specify various acoustic features to extract from the sound files. Finally, the solutions are indexed by the selected timbral attribute. For our preliminary development we chose to implement two timbral attributes to test the feasibility of our idea: brightness and roughness.

According to the available literature about the perception of brightness, this attribute is highly correlated with spectral centroid [18] [10] [31] [32]. To approximate the level of brightness of the solutions, we decided to calculate the spectral centroid of each sound file. For a power spectrum with components $P_i(f_i)$, the spectral centroid F_c is defined as

$$F_c = \frac{\sum f_i P_i}{\sum P_i} \tag{1}$$

and F_c is a frequency. The highest the frequency is, the brighter the sound is. Hence, we index the solutions, by their spectral centroid, from the brightest to the least bright.

For the second timbral attribute, we chose to implement the perception of roughness. This timbral quality is correlated with beats between two partials of a sound, critical bands and partials above the 6th harmonic [15] [37] [4] [33]. We decided to use the *mirroughness* function from the *MIRtoolbox v1.6.1*[4] [22] that integrates a set of functions written in *Matlab*[5]. The *mirrgouhness* function implements three methods of estimating the roughness of a sound. The first method is based on an estimation proposed by Sethares [33]. The second method is a variant of the Sethares model proposed by Weisser and Lartillot [39]. The last method is also a variant of the Sethares model developed by Vassilakis [38].

[4] MIRtoolbox is available at https://goo.gl/d61EO0
[5] http://www.mathworks.com/products/matlab

As per the brightness algorithm, we index the solutions from the roughest sound to the least rough sound, based on their respective roughness value.

4 Final Remarks

In this paper, we surveyed the evolution of the computer-assisted orchestration field, initiated by the spectral music movement in the early 1970s. Several composers associated to the spectral movement, including Gérard Grisey, Tristan Murail or Johannes Fritsch to name but three, started to work on the spectrum of sound using emerging technology to help them to achieve their compositions for ensembles or orchestra. Timbre, defined in section 3.1, plays an important part in the process of writing for an orchestra, as it involves several instruments that play simultaneously.

During the last ten years, some researchers proposed a few computer-aided orchestration systems that work with a target file (audio file or abstract) and a database of instruments, containing only instrumental proprieties or analysed and indexed audio samples. The user has the ability to specify the composition of the desired orchestra. These systems analyse the target, try to match the characteristics with the instrumental information contained in the database and then output the orchestration solutions.

We believe that one of the next areas of development for computer-aided orchestration systems is to focus on the orchestration solutions. An area of research could be to try to propose solutions related to the musical idea of the user, and not to propose all the correct solutions in terms of instrument mixture. The path we decided to take to filter the solutions is by using verbal descriptors of timbral qualities. This gives the user the ability to guide the system to output the solutions that match their ideal kind of sound.

Our preliminary implementation uses solutions generated by *Orchids*. Our system analyses the sound files and extracts acoustic features related to two timbral attributes: brightness and roughness. After the analysis is done, the solutions are indexed from the brightest or roughest sound to the least bright or rough sound. The next step for our system is to implement more timbral attributes and to test our indexing efficiency. Furthermore, in terms of computational efficiency, this method of filtering would be better implemented directly in the searching algorithm of the computer-assisted orchestration system, instead of doing the analysis and classification afterwards.

Another approach to personalise the solutions proposed by these systems could be to learn the preferences of the user/composer in order to propose solutions related to his or her musical style. Adding an artificial intelligence approach in computer-assisted orchestration systems could be beneficial to improve the generated solutions. These ideas need to be explored to move towards more intelligent orchestration systems.

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References

1. Adler, S.: The Study of Orchestration–3rd Edition. WW Norton (2002)
2. American Standards Association: Acoustical Terminology, Definition 12.9, Timbre (1960)
3. Assayag, G., Rueda, C., Laurson, M., Agon, C., Delerue, O.: Computer-assisted composition at ircam: From patchwork to openmusic. Computer Music Journal 23(3), 59–72 (1999)
4. Aures, v.W.: A procedure for calculating auditory roughness. Acustica 58(5), 268–281 (1985)
5. Barlow, C.: On the spectral analysis of speech for subsequent resynthesis by acoustic instruments. In: Forum phoneticum. vol. 66, pp. 183–190. Hector (1998)
6. Barrière, J.B.: Le Timbre: métaphore pour la composition. Christian Bourgois (1991)
7. Berlioz, H.: Traité d'instrumentation et d'orchestration. Henri Lemoine, Paris, 2e edn. (1855)
8. Carpentier, G.: Approche computationnelle de l'orchestration musicale. Ph.D. thesis, Université Pierre et Marie Curie (UMPC) et IRCAM, Paris (2008)
9. Carpentier, G., Bresson, J.: Interacting with symbol, sound, and feature spaces in orchidée, a computer-aided orchestration environment. Computer Music Journal 34(1), 10–27 (2010)
10. Disley, A.C., Howard, D.M., Hunt, A.D.: Timbral description of musical instruments. In: International Conference on Music Perception and Cognition. pp. 61–68 (2006)
11. Dufourt, H.: Musique spectrale: pour une pratique des formes de l'énergie. Bicéphale (3), 85–89 (1981)
12. Erickson, R.: Sound structure in music. Univ of California Press (1975)
13. Esling, P.: Multiobjective time series matching and classification. Ph.D. thesis, Université Pierre et Marie Curie (UMPC) et IRCAM, Paris (2012)
14. Esling, P., Bouchereau, A.: Orchids: Abstract and temporal orchestration software. IRCAM, Paris, first edn. (November 2014)
15. Fastl, H., Zwicker, E.: Psychoacoustics: Facts and models, vol. 22. Springer Science & Business Media (2007)
16. Hiller, L., Isaacson, L.: Experimental music: composition with an electronic computer. McGraw-Hill, Inc, New-York (1959)
17. Hummel, T.A.: Simulation of human voice timbre by orchestration of acoustic music instruments. In: Proceedings of International Computer Music Conference (ICMC). p. 185 (2005)
18. Johnson, C.G., Gounaropoulos, A.: Timbre interfaces using adjectives and adverbs. In: Proceedings of the 2006 conference on New interfaces for musical expression. pp. 101–102. IRCAM—Centre Pompidou (2006)
19. Kennan, K.: The technique of orchestration. Prentice Hall, New Jersey (1952)
20. Koechlin, C.: Traité de l'Orchestration. Max Eschig, Paris (1943)

21. Krumhansl, C.L.: Why is musical timbre so hard to understand. Structure and perception of electroacoustic sound and music 9, 43–53 (1989)
22. Lartillot, O.: MIRtoolbox 1.6.1 User's Manual. Aalborg University, Denmark (2014)
23. Malherbe, C.: The OM Composer's Book, vol. 2, chap. Locus: rien n'aura eu lieu que le lieu. Editions Delatour, France (2008)
24. Maresz, Y.: On computer-assisted orchestration. Contemporary Music Review 32(1), 99–109 (2013)
25. Nouno, G., Cont, A., Carpentier, G., Harvey, J.: Making an orchestra speak. In: Sound and Music Computing (SMC). Porto, Portugal (2009)
26. Pennycook, B.W.: Computer-music interfaces: a survey. ACM Computing Surveys (CSUR) 17(2), 267–289 (1985)
27. Poller, T.R.: Clarence barlow's: Technique of 'synthrumentation' and its use in im januar am nil. Tempo 69(271), 7–23 (January 2015)
28. Psenicka, D.: Sporch: An algorithm for orchestration based on spectral analyses of recorded sounds. In: Proceedings of International Computer Music Conference (ICMC). p. 184 (2003)
29. Roads, C.: The computer music tutorial. MIT press (1996)
30. Rose, F., Hetrick, J.: Spectral analysis as a ressource for contemporary orchestration technique. In: Proceedings of Conference on Interdisciplinary Musicology. vol. 2005 (2005)
31. Schubert, E., Wolfe, J.: Does timbral brightness scale with frequency and spectral centroid? Acta acustica united with acustica 92(5), 820–825 (2006)
32. Schubert, E., Wolfe, J., Tarnopolsky, A.: Spectral centroid and timbre in complex, multiple instrumental textures. In: Proceedings of the international conference on music perception and cognition, North Western University, Illinois. pp. 112–116 (2004)
33. Sethares, W.A.: Tuning, timbre, spectrum, scale. Springer (1998)
34. Smalley, D.: Defining timbre—refining timbre. Contemporary Music Review 10(2), 35–48 (1994)
35. Tardieu, D.: Modèles d'instruments pour l'aide à l'orchestration. Ph.D. thesis, Université Pierre et Marie Curie (UMPC) et IRCAM, Paris (2008)
36. Tardieu, D., Carpentier, G., Rodet, X.: Computer-aided orchestration based on probabilistic instruments models and genetic exploration. In: Proceedings of International Computer Music Conference, Copenhagen, Denmark (2007)
37. Terhardt, E.: On the perception of periodic sound fluctuations (roughness). Acta Acustica united with Acustica 30(4), 201–213 (1974)
38. Vassilakis, P.N.: Perceptual and physical properties of amplitude fluctuation and their musical significance. Ph.D. thesis, University Of California, Los Angeles (2001)
39. Weisser, S., Lartillot, O.: Investigating non-western musical timbre: a need for joint approaches. 3rd International Workshop on Folk Music Analysis (2013)
40. Williams, D.: Towards a Timbre Morpher. Ph.D. thesis, University of Surrey (2010)