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Activity Report 2013

Project-Team MUTANT

Synchronous Realtime Processing and Programming of Music Signals

RESEARCH CENTER
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THEME
Embedded and Real-time Systems

Table of contents

Project-Team MUTANT

Keywords: Audio, Domain-specific Languages, Machine Learning, Real-time, Signal Processing, Model Of Computation

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2. Overall Objectives

2.1. Overall Objectives

The research conducted in *MuTant* is devoted both to leveraging capabilities of musical interactions between humans and computers, and to the development of tools to foster the authoring of interaction and time in computer music. Our research program departs from *Interactive music systems* for computer music composition and performance introduced in mid-1980s at Ircam. Within this paradigm, the computer is brought into the cycle of musical creation as an *intelligent performer* [53] and equipped with a *listening machine* [49] capable of analyzing, coordinating and anticipating its own and other musicians' actions within a musically coherent and synchronous context. Figure 1 illustrates this paradigm. The use of Interactive Music Systems have become universal ever since and their practice has not ceased to nourish multidisciplinary research. From a research perspective, an interactive music systems deals with two problems: realtime machine listening [48], [49] or music information retrieval from musicians on stage, and music programming paradigms [43], [36] reactive to the realtime recognition and extraction. Whereas each field has generated subsequent literature, few attempts have been made to address the global problem by putting the two domains in direct interaction.

In modern practices, the computer's role goes beyond rendering pre-recorded accompaniments and is replaced by concurrent, synchronous and realtime programs defined during the compositional phase by artists and programmers. This context is commonly referred to as *Machine Musicianship* where the computer does not blindly follow the human but instead has a high degree of musical autonomy and competence. In this project, we aim at developing computer systems and language to support real-time intelligent behavior for such interactions.

Figure 1. General scheme of Interactive Music Systems

MuTant's research proposal lies at the intersection and union of two themes, often considered as disjoint but inseparable within a musical context:

1. Realtime music information retrieval and processing
2. Synchronous and realtime programming for computer music

2.2. Highlights of the Year

Figure 2. Antescofo presentation and demo in Bercy, Ministry of Industry.

Antescofo has been awarded the Industry prize by the French Minister of Industry, for its R&D and upcoming industrial applications.

Antescofo has been presented at the MIF Show (salon Made In France) invited by the ministère du redressement productif (November 2013).

Invited Demonstration at the 10th anniversary of La Recherche Prize.

3. Research Program

3.1. Real-time Machine Listening

When human listeners are confronted with musical sounds, they rapidly and automatically find their way in the music. Even musically untrained listeners have an exceptional ability to make rapid judgments about music from short examples, such as determining music style, performer, beating, and specific events such as instruments or pitches. Making computer systems capable of similar capabilities requires advances in both music cognition, and analysis and retrieval systems employing signal processing and machine learning.

In a panel session at the 13th National Conference on Artificial Intelligence in 1996, Rodney Brooks (noted figure in robotics) remarked that while automatic speech recognition was a highly researched domain, there had been few works trying to build machines able to understand "non-speech sound". He went further to name this as one of the biggest challenges faced by Artificial Intelligence [50]. More than 15 years have passed. Systems now exist that are able to analyze the contents of music and audio signals and communities such as International Symposium on Music Information Retrieval (MIR) and Sound and Music Computing (SMC) have formed. But we still lack reliable Real-Time machine listening systems.

The first thorough study of machine listening appeared in Eric Scheirer's PhD thesis at MIT Media Lab in 2001 [49] with a focus on low-level listening such as pitch and musical tempo, paving the way for a decade of research. Since the work of Scheirer, the literature has focused on task-dependent methods for machine listening such as pitch estimation, beat detection, structure discovery and more. Unfortunately, the majority of existing approaches are designed for information retrieval on large databases or off-line methods. Whereas the very act of listening is real-time, very little literature exists for supporting real-time machine listening. This argument becomes more clear while looking at the yearly Music Information Retrieval Evaluation eXchange (MIREX), with different retrieval tasks and submitted systems from international institutions, where almost no emphasis exists on real-time machine listening. Most MIR contributions focus on off-line approaches to information retrieval (where the system has access to future data) with less focus on on-line and realtime approaches to information decoding.

On another front, most MIR algorithms suffer from modeling of temporal structures and temporal dynamics specific to music (where most algorithms have roots in speech or biological sequence without correct adoption to temporal streams such as music). Despite tremendous progress using modern signal processing and statistical learning, there is much to be done to achieve the same level of abstract understanding for example in text and image analysis on music data. On another hand, it is important to notice that even untrained listeners are easily able to capture many aspects of formal and symbolic structures from an audio stream in realtime. Realtime machine listening is thus still a major challenge for artificial sciences that should be addressed both on application and theoretical fronts.

In the MuTant project, we focus on realtime and online methods of music information retrieval out of audio signals. One of the primary goals of such systems is to fill in the gap between *signal representation* and *symbolic information* (such as pitch, tempo, expressivity, etc.) contained in music signals. MuTant's current activities focus on two main applications: *score following* or realtime audio-to-score alignment [2], and realtime transcription of music signals [26] with impacts both on signal processing using machine learning techniques and their application in real-world scenarios.

The team-project focuses on two aspects of realtime machine listening:

1. **Application-Driven Approach:** First, to enhance and foster existing application-driven approaches within the team such as realtime alignment algorithms and polyphonic pitch transcription. Our contributions on this line correspond to extensions of existing algorithmic approaches to realtime audio alignment and transcription to create new interactive application paradigms with new algorithmic approaches.
2. **Music Information Geometry:** In parallel to concrete applications, we hope to theoretically contribute to the problem of signal representations of audio streams for effortless retrieval of high-level information structures. We have shown in [4] that the gap between the symbolic/semantic and signal aspects of music information mostly lies on constructing a well-behaved representational space before any algorithmic considerations, by employing the emerging methods of *information*

geometry.

3.2. Synchronous and realtime programming for computer music

The second aspect of an interactive music system is to *react* to extracted high-level and low-level music information based on pre-defined actions. The simplest scenario is *automatic accompaniment*, delegating the interpretation of one or several musical voices to a computer, in interaction with a live solo (or ensemble) musician(s). The most popular form of such systems is the automatic accompaniment of an orchestral recording with that of a soloist in the classical music repertoire (concertos for example). In the larger context of interactive music systems, the "notes" or musical elements in the accompaniment are replaced by "programs" that are written during the phase of composition and are evaluated in realtime in reaction and relative to musicians' performance. The programs in question here can range from sound playback, to realtime sound synthesis by simulating physical models, and realtime transformation of musician's audio and gesture.

Such musical practice is commonly referred to as the *realtime school* in computer music, developed naturally with the invention of the first score following systems, and led to the invention of the first prototype of realtime digital signal processors [38] and subsequents [42], and the realtime graphical programming environment *Max* for their control [46] at Ircam. With the advent and availability of DSPs in personal computers, integrated realtime event and signal processing graphical language *MaxMSP* was developed [47] at Ircam, which today is the worldwide standard platform for realtime interactive arts programming. This approach to music making was first formalized by composers such as Philippe Manoury and Pierre Boulez, in collaboration with researchers at Ircam, and soon became a standard in musical composition with computers.

Besides realtime performance and implementation issues, little work has underlined the formal aspects of such practices in realtime music programming, in accordance to the long and quite rich tradition of musical notations. Recent progress has convinced both the researcher and artistic bodies that this programming paradigm is close to *synchronous reactive programming languages*, with concrete analogies between both: parallel synchrony and concurrency is equivalent to musical polyphony, periodic sampling to rhythmic patterns, hierarchical structures to micro-polyphonies, and demands for novel hybrid models of time among others. *Antescofo* is therefore an early response to such demands that needs further explorations and studies.

Within the MuTant project, we propose to tackle this aspect of the research within two consecutive lines:

- **Development of a Timed and Synchronous DSL for Real Time Musician-Computer Interaction:** Ongoing and continuous extensions of the *Antescofo* language following user requests and by inscribing them within a coherent framework for the handling of temporal musical relationships. José Echeveste's ongoing PhD thesis focuses on the research and development of these aspects.
- **Formal Methods:** Failure during an artistic performance should be avoided. This naturally leads to the use of formal methods, like static analysis, verification or test generation, to ensure formally that *Antescofo* programs will behave as expected on stage. The checked properties may also provide some assistance to the composer especially in the context of "non deterministic score" in an interactive framework. The recently started PhD of Clément Poncelet is devoted to these problems.

3.3. Off-the-shelf Operating Systems for Real-time Audio

While operating systems shield the computer hardware from all other software, it provides a comfortable environment for program execution and evades offensive use of hardware by providing various services related to essential tasks. However, integrating discrete and continuous multimedia data demands additional services, especially for real-time processing of continuous-media such as audio and video. To this end interactive systems are sometimes referred to as off-the-shelf operating systems for real-time audio. The difficulty in providing correct real-time services has much to do with human perception. Correctness for real-time audio is more stringent than video because human ear is more sensitive to audio gaps and glitches than human eye is to video jitter [52]. Here we expose the foundations of existing sound and music operating systems and focus on their major drawbacks with regards to today practices.

An important aspect of any real-time operating system is fault-tolerance with regards to short-time failure of continuous-media computation, delivery delay or missing deadlines. Existing multimedia operating systems are soft real-time where missing a deadline does not necessarily lead to system failure and have their roots in pioneering work in [51]. Soft real-time is acceptable in simple applications such as video-on-demand delivery, where initial delay in delivery will not directly lead to critical consequences and can be compensated (general scheme used for audio-video synchronization), but with considerable consequences for Interactive Systems: Timing failure in interactive systems will heavily affect inter-operability of models of computation, where incorrect ordering can lead to unpredictable and unreliable results. Moreover, interaction between computing and listening machines (both dynamic with respect of internal computation and physical environment) requires tighter and explicit temporal semantics since interaction between physical environment and the system can be continuous and not demand-driven.

Fulfilling timing requirements of continuous media demands explicit use of scheduling techniques. As shown earlier, existing Interactive Music Systems rely on combined event/signal processing. In real-time, scheduling techniques aim at gluing the two engines together with the aim of timely delivery of computations between agents and components, from the physical environment, as well as to hardware components. The first remark in studying existing system is that they all employ static scheduling, whereas interactive computing demands more and more time-aware and context-aware dynamic methods. The scheduling mechanisms are neither aware of time, nor the nature and semantics of computations at stake. Computational elements are considered in a functional manner and reaction and execution requirements are simply ignored. For example, *Max* scheduling mechanisms can delay message delivery when many time-critical tasks are requested within one cycle [47]. *SuperCollider* uses Earliest-Deadline-First (EDF) algorithms and cycles can be simply missed [45]. This situation leads to non-deterministic behavior with deterministic components and poses great difficulties for preservation of underlying techniques, art pieces, and algorithms. The situation has become worse with the demand for nomad physical computing where individual programs and modules are available but no action coordination or orchestration is proposed to design integrated systems. System designers are penalized for expressivity, predictability and reliability of their design despite potentially reliable components.

Existing systems have been successful in programing and executing small system comprised of few programs. However, severe problems arise when scaling from program to system-level for moderate or complex programs leading to unpredictable behavior. Computational elements are considered as functions and reaction and execution requirements are simply ignored. System designers have uniformly chosen to hide timing properties from higher abstractions, and despite its utmost importance in multimedia computing, timing becomes an accident of implementation. This confusing situation for both artists and system designers, is quite similar to the one described in Edward Lee's seminal paper "Computing needs time" stating: "general-purpose computers are increasingly asked to interact with physical processes through integrated media such as audio. [...] and they don't always do it well. The technological basis that engineers have chosen for general-purpose computing [...] does not support these applications well. Changes that ensure this support could improve them and enable many others" [41].

Despite all shortcomings, one of the main advantages of environments such as *Max* and *PureData* to other available systems, and probably the key to their success, is their ability to handle both synchronous processes (such as audio or video delivery and processing) within an asynchronous environment (user and environmental interactions). Besides this fact, multimedia service scheduling at large has a tendency to go more and more towards computing besides mere on-time delivery. This brings in the important question of hybrid scheduling of heterogeneous time and computing models in such environments, a subject that has had very few studies in multimedia processing but studied in areas such simulation applications. We hope to address this issue scientifically by first an explicit study of current challenges in the domain, and second by proposing appropriate methods for such systems. This research is inscribed in the three year ANR project INEDIT coordinated by the team leader (started in September 2012).

4. Application Domains

4.1. Authoring and Performing Interactive Music

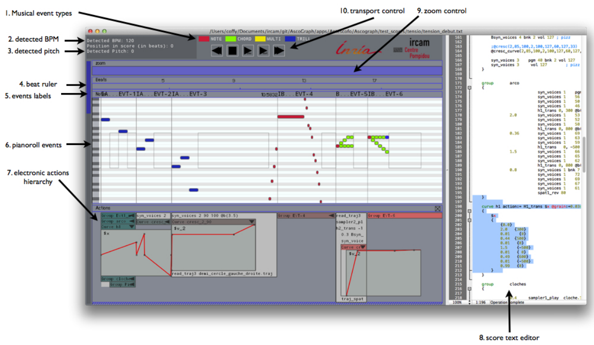

Figure 3. Screenshot of Ascograph, the Antescofo graphical score editor

The combination of both realtime machine listening systems and reactive programming paradigms has enabled the *authoring* of interactive music systems as well as their realtime performance within a coherent synchronous framework called Antescofo. The module, developed since 2008 by the team members, has gained increasing attention within the user community worldwide with more than 40 prestigious public performances yearly. The outcomes of the teams's research will enhance the interactive and reactive aspects of this emerging paradigm as well as creating novel authoring tool for such purposes. The *AscoGraph* authoring environment developed in 2013 and shown in Figure 3 is the first step towards such authoring environments. The outcome of the ANR Project INEDIT (with LABRI and GRAME and coordinated by team leader), will further extend the use-cases of *Antescofo* for interactive multimedia pieces with more complex temporal structures and computational paradigms.

4.2. Music Post-Production.

Outcomes of our recognition and alignment paradigms can improve and ease existing workflows employed by audio engineers for mixing and editing using commercial Digital Audio Workstations (DAW) in post-production. We have initiated collaborations with audio engineers at Ircam and Paris Superior Music Conservatory (CNSMDP) to define the framework [9] and we will continue to develop and integrate our tools into their daily workflow.

4.3. Realtime Music Information Retrieval

We are considering to apply our information geometric approach to well-known and complex MIR problems. A glance of such problems is presented in [6]. Such applications can be used as front-end of many high-level MIR applications such as audio summarisation, audio finger printing, and automatic annotation tools. Besides such low-level enhancements, our information geometric approach can address the well-known (and still to be solved) problem of audio queries over a database.

4.4. Automatic Accompaniment/Creative Tools for Entertainment Industry

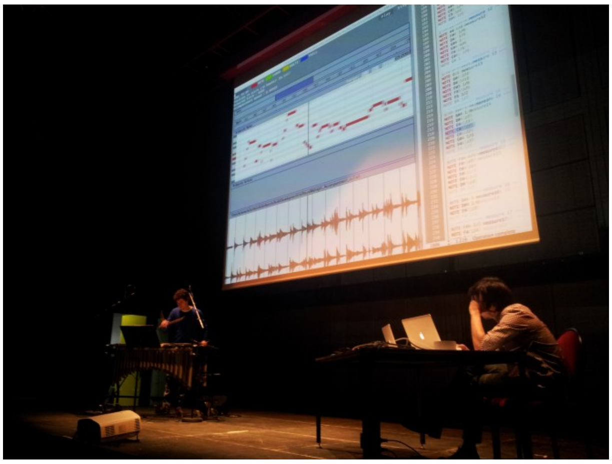

Figure 4. Automatic Accompaniment Session with Antescofo during ACM CHI 2013 Conference

Technologies developed by MuTant can find their way with general public (besides professional musicians) and within the entertainment industry. Recent trends in music industry show signs of tendencies towards more intelligent and interactive interfaces for music applications. Among them is reactive and adaptive automatic accompaniment and performance assessment as commercialized by companies such as *MakeMusic* and *Tonara*. Technologies developed around *Antescofo* can enhance interaction between user and the computer for such large public applications. We hope to pursue this by licensing our technologies to third-party companies.

5. Software and Platforms

5.1. Antescofo

Participants: Arshia Cont, Jean-Louis Giavitto, Florent Jacquemard, José Echeveste.

Antescofo is a modular polyphonic Score Following system as well as a Synchronous Programming language for musical composition. The module allows for automatic recognition of music score position and tempo from a realtime audio Stream coming from performer(s), making it possible to synchronize an instrumental performance with computer realized elements. The synchronous language within Antescofo allows flexible writing of time and interaction in computer music.

Antescofo is developed as modules for *Max* and *PureData* real-time programming environments.

A complete new version of Antescofo has been released on November 2013 on Ircam Forumnet. This version is the result of one year of intensive effort by MuTant team members and associate artists.

This release include major improvements on the reactive language: richer set of synchronization strategies and control structures, dynamic continuous actions, high order function and processes, historicized variables and dynamic expressions everywhere (delays or periods as variables or expressions).

The new internal architecture unifies completely the handling of external (musical) events and the handling of internal (logical) events in a framework able to manage multiple time frames (relative, absolute or computed).

The new version targets the Max and PureData (Pd) environments on Mac, but also on Linux (Pd version) and offers also a standalone offline version. The standalone version is used to simulate a performance in Ascograph.

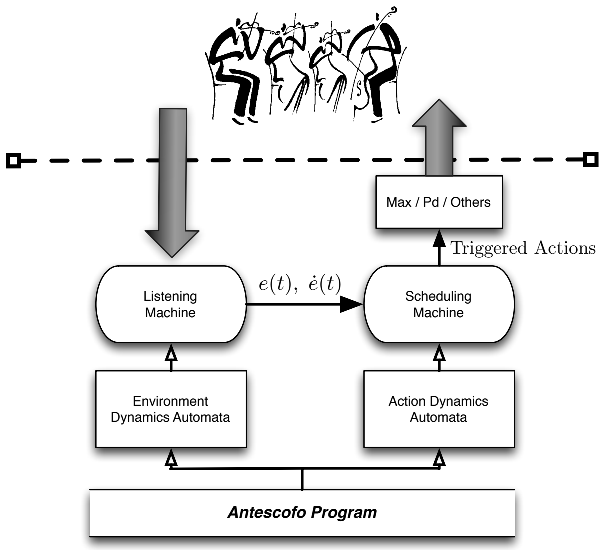

Figure 5. General scheme of Antescofo virtual machine

An important enhancement has been made by proposing a richer set of synchronization strategies between the event recognized by the listening machine and the action to be performed by the reactive engines. Theses new strategies include *anticipative* strategies that exhibits a smoother musical behavior. These strategies are now tested in various musical situations like accompaniments and in the creation of new pieces.

Some new results including a behavioral semantics of the static kernel of the Antescofo reactive engine [17] and tools for formal verification and conformance testing of the system [24], [35] are presented below.

5.2. Ascograph: Antescofo Visual Editor

Participants: Thomas Coffy [ADT], Arshia Cont, José Echeveste.

The Antescofo programming language can be extended to visual programing to better integrate existing scores and to allow users to construct complex and embedded temporal structures that are not easily integrated into text. This project is held since October 2012 thanks to Inria ADT Support.

AscoGraph, the new Antescofo graphical score editor has been released this year. It provides a autonomous Integrated Development Environment (IDE) for the authoring of Antescofo scores. Antescofo listening machine, when going forward in the score during recognition, uses the message passing paradigm to perform tasks such as automatic accompaniment, spatialization, etc. The Antescofo score is a text file containing notes (chord, notes, trills, ...) to follow, synchronization strategies on how to trigger actions, and electronic actions (the reactive language). This editor shares the same score parsing routines with Antescofo core, so the validity of the score is checked on saving while editing in AscoGraph, with proper parsing errors handling. Graphically, the application is divided in two parts (see Figure 3). On the left side, a graphical representation of the score, using a timeline with tracks view. On the right side, a text editor with syntax coloring of the score is displayed. Both views can be edited and are synchronized on saving. Special objects such as "curves", are graphically editable: they are used to provide high-level variable automation facilities like breakpoints functions (BPF) with more than 30 interpolations possible types between points, graphically editable.

One other really important feature is the score import from MusicXML or MIDI files, which make the complete workflow of the composition of a musical piece much easier than before.

AscoGraph is strongly connected with Antescofo core object (using OSC over UDP): when a score is edited and modified it is automatically reloaded in Antescofo, and on the other hand, when Antescofo follows a score (during a concert or rehearsal) both graphical and textual view of the score will scroll and show the current position of Antescofo.

AscoGraph is released under Open-Source MIT license and has been released publicly along with new Antescofo architecture during IRCAM Forum 2013.

6. New Results

6.1. Operational Timed Semantics

Participants: José Echeveste, Jean-Louis Giavitto, Florent Jacquemard, Arshia Cont.

One common use-case of real-time musical interactions between musicians and computers is *Automatic Accompaniment* where the system is comprised of a real-time machine listening system that in reaction to recognition of events in a score from a human performer, launches necessary actions for the accompaniment section. While the real-time detection of score events out of live musicians' performance has been widely addressed in the literature, score accompaniment (or the reactive part of the process) has been rarely discussed. In [13], we are trying to deal with this missing component in the literature from a programming language perspective. We show how language considerations would enable better authoring of time and interaction during programming/composing and how it addresses critical aspects of a musical performance (such as errors) in real-time. We sketch the real-time features required by automatic musical accompaniment seen as a reactive system and formalize the timing strategies for musical events taking into account the various temporal scales used in music. Various strategies for the handling of synchronization constraints and the handling of errors are presented.

The behavior of the system *Antescofo* have been formally modeled as a *network of parametric timed automata*. The model obtained provides operational semantics for the input scores, in particular the interaction between the instrumental and electronic parts and the timing and error handling strategies mentioned below. This approach enables better authoring of time and interaction during programing/composing, permitting to use state of the art software verification tools for the static analysis of Antescofo scores. It also provides means to address critical aspects of musical performances in real-time.

6.2. Timed Static Analysis of Interactive Music Scores

Participant: Florent Jacquemard.

It is well known that every musician performance of the same work will differ from another. It is therefore a challenging task to be able to predict the behavior of interactive music systems like *Antescofo* in response to any possible performance, and prevent unwanted outcomes. With Léa Fanchon, we have been working on a module for timing analysis of augmented scores that complements the real-time score authoring and performance in *Antescofo*, with the aim of exploring possible behavior of authored scores with respect to possible deviations in human musician performance.

For this purpose we have studied [24] the application of formal models and methods from the literature of real-time systems verification to the static analysis of interactive music systems. We have considered in particular the good parameters problem, which consists in synthesizing a set of timing parameter valuations (representing performances here) guarantying a good behavior of the system analyzed. The methods presented in [24] have been applied to *Antescofo*, providing the following input to users:

- Evaluation of robustness of the program with respect to the environment's (musician's performance) temporal variations,
- Feedback to programmers or artists on critical synchronization points for better programming.

This study is one of the first of this kind in computer music literature, and the methods presented are general enough to apply to the verification of other interactive multimedia applications.

6.3. Automating the Generation of Test Suites for Antescofo

Participants: Florent Jacquemard, Clément Poncelet.

Clément Poncelet has started to develop during his Master thesis [35] a framework for black box conformance testing of *Antescofo*. This work is pursued in a PhD supported by DGA and Inria. The most important task in this context is the generation of relevant test data for the system, given an augmented score in *Antescofo* language. This data includes input, containing musical events (notes, chords etc) together with their timings. In a sense, the input data simulates a musical execution of the score. The input data must then be passed to *Antescofo* for black-box execution, in order to observe the system's reactions and compare them the expected output. For the latter comparison task, we need to be able to define the expected output, hence to have a formal model of the expected behavior of the system on the given score. For this purpose, we are using models of the system made of timed automata, which are computed automatically from given music scores. Then, we use tools from the UPPAAL suite [40] in order to generate testing data, based on relevant covering criteria and a formal model of the environment (i.e. the musician). This work has been presented at the poster session of MSR 2013 (national colloquium on modeling reactive systems) and a journal paper is in preparation.

6.4. Synchronous Embedding of Antescofo DSL

Participants: Arshia Cont, Jean-Louis Giavitto, Florent Jacquemard.

Antescofo can been seen as the coupling of a listening machine and a real-time reactive system. Therefore, it faces some of the same major challenges as embedded systems. We have been working with Guillaume Baudart, Louis Mandel, and Marc Pouzet (EPI Parkas, ENS) in strengthening the ties between the reactive aspects of *Antescofo* and that of synchronous languages, in particular ReactiveML [44]. In [17], we present a synchronous semantics for the core language of Antescofo and an alternative implementation, based on an embedding inside the synchronous language ReactiveML [44]. The semantics reduces to a few rules, is mathematically precise and leads to an interpretor of a few hundred lines whose efficiency compares well with that of the current implementation. On all musical pieces we have tested, response times have been less than the reaction time of the human ear. Moreover, this embedding permitted the prototyping of several new programming constructs. Some examples are available, together with the ReactiveML source code at http://reactiveml.org/emsoft13/.

6.5. Tree Structured Representation of Symbolic Temporal Data

Participant: Florent Jacquemard.

In traditional music notation, in particular in the languages used for the notation of mixed music such as Antescofo DSL, the durations are not expressed by numerical quantities but by symbols representing successive subdivisions of a reference time value (the beat). For this reason, trees data structures are commonly used for the symbolic representation of rhythms in computer aided composition softwares such as OpenMusic (developed at Ircam).

Following this idea, we have been working on using several tree automata techniques for the challenging and long-standing problem of automatic transcription of rhythm (in traditional music notations) from symbolic input data (symbolic traces with timestamps in ms, like e.g. in MIDI format). To summarize, the main problem in rhythm transcription is to find an acceptable balance between timing precision (the goal is to minimize the loss obtained by transformation of ms timing values into fractions of beats) and the complexity of the notation obtained. The relative importance of these two measures may vary largely according to the user (composer), his workflow, and the musical style considered. It is therefore important to be able to control this balance during the transcription process, in order to adapt to the case of users. In traditional approaches, the transcription is done by an alignement of the input trace on a grid, and the two measures (precision of the grid and complexity) are either defined by parameters fixed a priori or hardcoded e.g. for a precise musical style and composition workflow. During two internships co-supervised by Jean Bresson (Ircam, main developer of OpenMusic) and Florent Jacquemard, we have been studying more flexible new approaches, based on computations on the tree representation of rhythms.

Pierre Donat-Bouillud (L3 ENS Rennes) [29] has worked on an approach by transformation of trees following some rewrite rules. The general idea is to start with a complex tree representing timings very close to the input data, and to simplify it by rewriting until an acceptable level of complexity is reached. The rewrite rules are either generic (defining an equational theory of rhythm notation) or user defined (defining approximations). This approach has been implemented in an OpenMusic library.

Adrien Maire (M1 ENS Cachan) has studied another very promising approach based on stochastic tree automata learning in an interactive authoring scenario. The generated automaton is supposed to represent (by the weighted tree langage it defines) the expected complexity of rhythm notations (i.e. the user's "style").

Moreover, we have following other work on several classes of tree recognizers and tree transformations which could be of interest in this context. With Luis Barguñó, Carlos Creus, Guillem Godoy, and Camille Vacher, [11] we define a class of ranked tree automata called TABG generalizing both the tree automata with local brother tests of Bogaert and Tison [37] and with global equality and disequality constraints (TAGED) of Filiot et al. [39]. TABG can test for equality and disequality modulo a given flat equational theory between brother subterms and between subterms whose positions are defined by the states reached during a computation. In particular, TABG can check that all the subterms reaching a given state are distinct. This constraint is related to monadic key constraints for XML documents, meaning that every two distinct positions of a given type have different values. We have proven decidability of the emptiness problem for TABG. This solves, in particular, the open question of decidability of emptiness for TAGED. We further extended our result by allowing global arithmetic constraints for counting the number of occurrences of some state or the number of different equivalence classes of subterms (modulo a given flat equational theory) reaching some state during a computation. We also adapt the model to unranked ordered terms. As a consequence of our results for TABG, we prove the decidability of a fragment of the monadic second order logic on trees extended with predicates for equality and disequality between subtrees, and cardinality.

With Michaël Rusinowitch (EPI Cassis), we have introduced in [25] an extension of unranked tree automata called bi-dimensional context-free hedge automata. The languages they define are context free in two dimensions: in the the sequence of successors of a node and also along paths. This formalism is useful for the static type-checking of tree transformations such as XML updates defined in the W3C XQuery Update Facility. We have developed with the same author in the past years a general framework for the verification of unranked (XML) tree transformations based on tree automata techniques. It has been presented this year in an invited keynote [16]. We have also presented with Emmanuel Filiot and Sophie Tison a survey on tree automata with constraints [33] during a Dagstuhl Seminar (number 13192) on tree transducers and formal methods.

6.6. Online Automatic Structure Discovery of Audio Signals

Participants: Arshia Cont, Vincent Lostanlen [MS Internship].

Following recent team findings in [12] and the framework introduced in [4], we pursued the problem of automatic discovery of audio signals using methods of information geometry through a Masters Thesis undertaken by Vincent Lostanlen (MS ATIAM) [34]. This work introduces a novel way of representing and calculating *Similarity Matrices* for continuous multimedia signals and in real-time. In this approach, the signal is first segmented into homogeneous chunks using the change detection algorithm proposed by the team in [12], and proposes a method for constituting similarity relations between segments using *Bregman Information Geometry* and exploiting intersections between information balls.

Compared to traditional approaches to similarity matrix computing, the approach proposed in [34] is strictly on-line (thus suitable for real-time computing) and provides a sparse view of audio structures. We will pursue this project by increasing its robustness and evaluating results on larger databases including other timed-signals such as video.

6.7. Temporal Coherency Criterion for Alignment Inference Algorithms

Participants: Philippe Cuvillier [PhD Student], Arshia Cont.

The question of modeling time and duration is of utmost importance for stability and robustness of real-time alignment algorithms and constitute one of the major success factors for the *Antescofo* listening machine described in [2]. Meanwhile, regular algorithms undergo stability in highly uncertain environments where observations obtained from the signal are highly uninformative and temporal information is of crucial importance.

PhD student Philippe Cuvillier defined *Coherency Criteria* for such applications and attempted to formalize such criteria in terms of probabilistic models and inference algorithms in case of Hidden Semi-Markov Chains. The results show that not all probabilistic families meet such criteria including some commonly used by engineers and designers. Preliminary results are submitted for publications and experimental results are being pursued.

7. Bilateral Contracts and Grants with Industry

7.1. Qwant

Together with Qwant, the MuTant team is in the process of defining and developing the Antescofo accompaniment engines for the entertainment industries on various mobile terminals.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

8.1.1.1. INEDIT

Title: Interactivity in the Authoring of Time and Interactions

Project acronym: INEDIT

Type: ANR Contenu et Interaction 2012 (CONTINT)

Instrument: ANR Grant

Duration: September 2012 - September 2015

Coordinator: IRCAM (France)

Other partners: Grame (Lyon, France), LaBRI (Bordeaux, France).

Abstract: The INEDIT project aims to provide a scientific view of the interoperability between common tools for music and audio productions, in order to open new creative dimensions coupling *authoring of time* and *authoring of interaction*. This coupling allows the development of novel dimensions in interacting with new media. Our approach lies within a formal language paradigm: An interactive piece can be seen as a virtual interpreter articulating locally synchronous temporal flows (audio signals) within globally asynchronous event sequence (discrete timed actions in interactive composition). Process evaluation is then to respond reactively to signals and events from an environment with heterogeneous actions coordinated in time and space by the interpreter. This coordination is specified by the composer who should be able to express and visualize time constraints and complex interactive scenarios between mediums. To achieve this, the project focuses on the development of novel technologies: dedicated multimedia schedulers, runtime compilation, innovative visualization and tangible interfaces based on augmented paper, allowing the specification and realtime control of authored processes. Among posed scientific challenges within the INEDIT project is the formalization of temporal relations within a musical context, and in particular the development of a GALS (Globally Asynchronous, Locally Synchronous) approach to computing that would bridge in the gap between synchronous and asynchronous constraints with multiple scales of time, a common challenge to existing multimedia frameworks.

8.1.2. Other National Initiatives

The team participated to the CLASYCO network on DSL for simulation, supported by the RNSC (réseau national des systèmes complexes).

Jean-Louis Giavitto participates to the SynBioTIC ANR Blanc project (with IBISC, University of Evry, LAC University of Paris-Est, ISC - Ecole Polytechnique).

8.2. International Initiatives

8.2.1. Inria International Partners

8.2.1.1. Informal International Partners

Miller Puckette (UCSD), David Wessel (UC Berkeley), Edward Lee (UC Berkeley), Shlomo Dubnov (UCSD).

8.3. International Research Visitors

Dr. Roger Dannenberg (Carnegie Mellon University) was invited by MuTant in May 2013, where he took part in Arshia Cont's HDR defense, José Echeveste's mid-term PhD defense, and gave a public seminar in the MuTant Seminars in Real-time Multimedia Computing series.

Dr. Shlomo Dubnoc (University of California San Diego) was invited by MuTant in August 2013 for ongoing collaborative work and to take part in the International Conference on Geometric Science of Information 2013, Special Session on *Audio and Music* organized by MuTant member Arshia Cont.

Masahiko Sakai visited MuTant for two weeks in August 2013. He is a professor at the University of Nagoya and director of the Sakabe/Sakai computer science laboratory of the department of computer science and mathematical informatics of Nagoya University.

Dr. Edward Lee and Dr. David Wessel (UC Berkeley) visited MuTant for discussions on future collaborations with MuTant around Cyber-Physical Systems.

9. Dissemination

9.1. Scientific Animation

MuTant acted as co-organizer and scientific chair for the first International Conference on Geometric Science of Information 2013 which took place in École des Mines (Paris) in partnership with SEE, and THALES. The conference attracted more than 150 participants worldwide and conference proceedings were published by Springer. MuTant team members organized a special session on Audio and Music and further organized a special social session on music computing at Ircam.

The Brillouin Seminar series on Information Geometry is coordinated by MuTant in partnership with LIX and THALES. It gathers 80 international researchers on the topic from various disciplines. In 2013, we organized 4 major talks. The seminar activity on 2013 was particularly down due to the co-organization of the first International Conference on the topic by MuTant and collaborators. Videos are available on the seminar website.

Jean-Louis Giavitto is in the management team of the GDR GPL (Genie de la programmation et du logiciel), responsible with Etienne Moreau of the "Languages and Ve´rification" pole of the GDR. He is also and expert for the ANR DEFI projects and a reviewer for FET projects for the UC. He is also the redactor-in-chief of TSI (Technique et Science Informatiques) published by Lavoisier.

Jean-Louis Giavitto has participated in the program committee of the following workshop and conferences: Rencontres interdisciplinaires de Rochebrune: ”La preuve et ses moyens” 13 au 19 janvier 2013; Digital Entertainment Technologies and Arts (DETA) track at GECCO 2013, 6-10 July 2013, Amsterdam, The Netherlands NICSO 2013 The VI International Workshop on Nature Inspired Cooperative Strategies for Optimization, September 2-4, 2013 Canterbury, United Kingdom; HaPoC 2013 2nd International Conference on the History and Philosophy of Computing 2013. 28th - 31st October 2013, 27/11/13 4/9 Ecole Normale Superieure, Paris; MeCBIC 2013 7th Workshop on Membrane Computing and Biologically Inspired Process Calculi, 7th July 2013, Riga, Latvia.

Jean-Louis Giavitto was cochair of the 6th Spatial Computing Workshop, satellite workshop of AAMAS 2013, Saint-Paul, USA.

Arshia Cont participated in the following events: Course in Collège de France, Informatics of Time and Events curated by Gérard Berry, June 2013; Invited keynote in Seoul (South Korea) on Antescofo, November 2013; Keynote in GSI, Grenoble in December 2013; Invited speech and demonstration for the 20th anniversary of Prix La Recherche; CHI workshop on Models of Time with Jean-Louis Giavitto and Florent Jacquemard, April 2013.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence : Arshia Cont, Audio Technology Review, 2h/week, L3, Paris Superior Conservatory of Music (CNSMDP), France.

Master : Arshia Cont, Machine Learning for Music, 15 hours, M2, UPMC/ATIAM, France.

Doctorat : Enseignant, titre du cours, nombre d’heures en équivalent TD, université, pays

Jean-Louis Giavitto has been invited to give a one week course on Spatial Computing at the University of Cali, Colombia (20 hours).

9.2.2. Supervision

PhD in progress :

José Echeveste, Synchronous Languages for Computer Music Composition and Performance, Started September 2011, co-directed by Jean-Louis Giavitto and Arshia Cont.

Philippe Cuvilier, Inference Mechanisms for on-line Machine Listening, Started September 2013, directed by Arshia Cont

Clement Poncelet, Formal analysis of human-machine interactions in complex timed scenarios. Started in October 2013, directed by Florent Jacquemard.

9.2.3. Juries

Florent Jacquemard participated in the selection committee to the 2013 recruitment campaign at the Inria center of Lille.

Florent Jacquemard participated to the defense committee for the PhD of Vincent Hugot, “Tree Automata, Approximations, and Constraints for Verification, Tree (Not-Quite) Regular Model-Checking”, University of Franche-Comté, September 2013. and to the mid-term PhD defense of Emil Mircea Andriescu on “Dynamic synthesis and deployment of mediation protocols in collaborative mobile environments”, a CIFRE agreement between UPMC, Inria and the SME Ambientic, in November 2013.

Jean-Louis Giavitto has expertised several project for the Ulysses Network http://www.ulysses-network.eu/web/home/; and has been reviewer of the PhD thesis of M. Obrovac (IRISA), A. Ajouli (LINA) and of the Habilitation of Arnaud Banos (Sorbonnes). He was also member of one selection committee for UPMC.

Figure 6. Antescofo demo in Ministry of Industry featuring Marlène Schaff (French THE VOICE, Season 2)

9.3. Popularization

MuTant team was featured in the 2nd edition of Made In France (MIF) Expo in the major Exhibition Hall in Paris (Porte de Versaille) with a dedicated stand for Antescofo with more than 3 million visitors during 3 days.

Antescofo was featured by the French Ministry of Industry for a public talk and largely diffused demo featuring the french star singer Marlène Schaff from *The Voice*.

Arshia Cont was invited for a public presentation/demo of *Antescofo* for the 20th anniversary of the Prix La Recherche. Click for video.

Jean-Louis Giavitto has co-animated the public discussion following the movie "Codebreaker: Alan Turing" with C. Villani and G. Berry at the Cinema Grand Action. He gave several seminars for a non computer scientist audience:

> “Analyse formelle des concepts, Q-analyse et programmation spatiale : quelques aspects philosophiques du nœud mathématique/musique/ informatique, séminaire MaMuPhi, l’Ecole Normale (february 2013);
>
> “Écriture du temps et de l’interaction en informatique musicale”, séminaire Philosophie de l’informatique, de la logique et de leurs interfaces, Centre Cavaillès, Ecole Normale, (mars 2013);
>
> “Modélisation spatiale et approche géométrique en musique”, Journées nationales du RNSC (octobre 2013);
>
> “Simultanéité, succession et durée dans l’interaction musicale en temps-réel”, séminaire MaMux Temps, rythme et arithmétique, (décembre 2013).
>
> As the redactor-in-chief of TSI, Jean-Louis Giavitto has initiated a new section devoted to portraits and talking with french personalities in computer science. These articles are also published in the SIF journal.

José Echeveste has presented Antescofo and participed to the event organized for the “Fête des Sciences” at Forum des Halles and UPMC.

We have published a popularization article on "Computer Assisted Music" in the review DocSciences, number 15.

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