

# Real-Time Musical Applications using FFT-based Resynthesis

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## Abstract

The Fast Fourier Transform (FFT) is a powerful general-purpose algorithm widely used in signal analysis. FFTs are useful when the spectral information of a signal is needed, such as in pitch tracking or vocoding algorithms. The FFT can be combined with the Inverse Fast Fourier Transform (IFFT) in order to resynthesize signals based on its analyses. This application of the FFT/IFFT is of great interest in electro-acoustic music because it allows for a high degree of control of a given signal's spectral information (an important aspect of timbre) allowing for flexible, and efficient implementation of signal processing algorithms. Real-time implementations of the FFT and IFFT are of particular interest since they may be used to provide musicians with highly responsive and straight-forward means for generating and controlling sound in live-performance situations. This paper presents musical applications using the IRCAM Signal Processing Workstation (ISPW) that make use of FFT/IFFT-based resynthesis for timbral transformation in real time. An intuitive and straightforward user interface, intended for use by musicians, has been developed by the authors in the Max programming environment. Techniques for filtering, cross-synthesis, noise reduction, dynamic spectral shaping, and resynthesis are presented along with control structures that allow for fine timbral modification and control of complex sound transformations using few parameters. Emphasis is also placed on developing control structures derived from real-time analyses (time and frequency domain) of a musician's input. The ideas and musical applications, discussed in this paper, offer composers an intuitive approach to timbral transformation in electro-acoustic music, and new possibilities in the domain of live signal processing that promise to be of general interest to musicians.

## 1. Introduction

The Fast Fourier Transform (FFT) is a powerful general-purpose algorithm widely used in signal analysis. FFTs are useful when the spectral information of a signal is needed, such as in pitch tracking or vocoding algorithms. The FFT can be combined with the Inverse Fast Fourier Transform (IFFT) in order to resynthesize signals based on its analyses. This application of the FFT/IFFT is of particular interest in electro-acoustic music because it allows for a high degree of control of a given signal's spectral information (an important aspect of timbre) allowing for flexible, and efficient implementation of signal processing algorithms.

This paper presents real-time musical applications using the IRCAM Signal Processing Workstation (ISPW) [Lindemann, Starkier, and Dechelle 1991] which make use of FFT/IFFT-based resynthesis for timbral transformation in a compositional context.

Taking a pragmatic approach, the authors have developed a user interface in the Max programming environment [Puckette, 1988] for the prototyping and development of signal processing applications intended for use by musicians. Techniques for filtering, cross-synthesis, noise reduction, and dynamic spectral shaping have been explored, as well as control structures derived from real-time signal analyses via pitch-tracking and envelope following [Lippe & Puckette 1991]. These real-time musical applications offer composers an intuitive approach to timbral transformation in electro-acoustic music, and new possibilities in the domain of live signal processing that promise to be of general interest to musicians.

## 2. The FFT in Real Time

Traditionally the FFT/IFFT has been widely used outside of real-time for various signal analysis/re-

synthesis applications that modify the durations and spectra of pre-recorded sound [Haddad & Parsons 1991]. With the ability to use the FFT/IFFT in real-time, live signal-processing in the spectral domain becomes possible, offering attractive alternatives to standard time-domain signal processing techniques. Some of these alternatives offer a great deal of power, run-time economy, and flexibility, as compared with standard time-domain techniques [Gordon & Strawn 1987]. In addition, the FFT offers both a high degree of precision in the spectral domain, and straightforward means for exploitation of this information. Finally, since real-time use of the FFT has been prohibitive for musicians in the past due to computational limitations of computer music systems, this research offers some relatively new possibilities in the domain of real time.

### **2.1 Programming Environment**

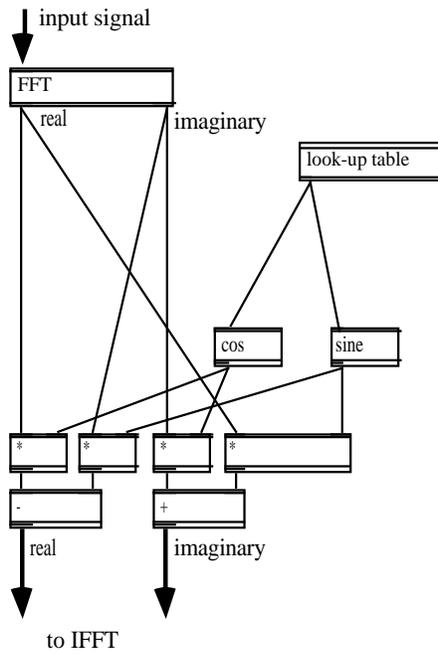
Our work up to this time has been focused on real-time signal processing applications involving the spectral modification of sounds. (We hope to attack the problem of time-stretching at a later date.) Since we are constructing our signal processing configurations in Max using a modular patching approach that includes both time-domain and frequency-domain modules, we are able to develop hybrids, discussed below, that combine standard modules of both types. Development in the Max programming environment [Puckette, 1991] tends to be simple and quite rapid: digital signal processing (DSP) programming in Max requires no compilation; control and DSP objects run on the same processor,

and the DSP library provides a wide range of unit generators, including the FFT and IFFT modules.

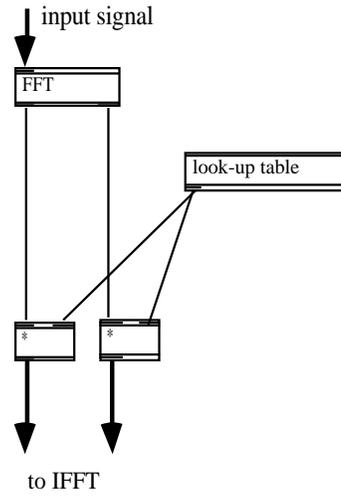
### **2.2 Algorithms and basic operations**

All of the signal processing applications discussed in this paper modify incoming signals and are based on the same general DSP configuration. Using an overlap-add technique, the DSP configuration includes the following steps: (1), windowing of the input signals, (2) transformation of the input signals into the spectral domain using the FFT, (3) operations on the signals' spectra, (4) resynthesis of the modified spectra using the IFFT, (5) and windowing of the output signal. Operations in the spectral domain include applying functions (often stored in tables), convolution (complex multiplication), addition, and taking the square root (used in obtaining an amplitude spectrum); data in this domain are in the form of rectangular coordinates. Due to the inherent delay introduced by the FFT/IFFT process, we use 512 point FFTs for live signal processing when responsiveness is important. Differences in the choice of spectral domain operations, kinds of input signals used, and signal routing determine the nature of a given application: small changes to the topology of the DSP configuration can result in significant changes to its functionality. Thus, we are able to reuse much of our code in diverse applications. For example, though functionally dissimilar, the following two applications differ only slightly in terms of their implementation.

**phase rotation**



**filtering**



*figure 1: differing applications with similar DSP implementation*

### 3. Applications

#### 3.1 High-resolution filtering

Highly detailed time varying spectral envelopes can be produced and controlled by relatively simple means. A look-up table can be used to describe a spectral envelope in the implementation of a graphic EQ of up to 512 bands. The spectrum of the input signal is convolved, point by point, with the data in the look-up table, producing a filtered signal. Because we are able to alter the spectral envelope in real time at the control rate (up to 1kHz), we may modify our spectral envelope graphically or algorithmically, hearing the results immediately.

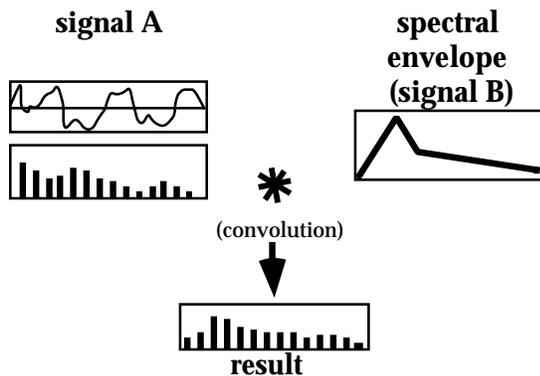


figure 2: filtering with a user-specified spectral envelope

Using a noise source as the input signal, it is also possible to do *subtractive synthesis* efficiently.

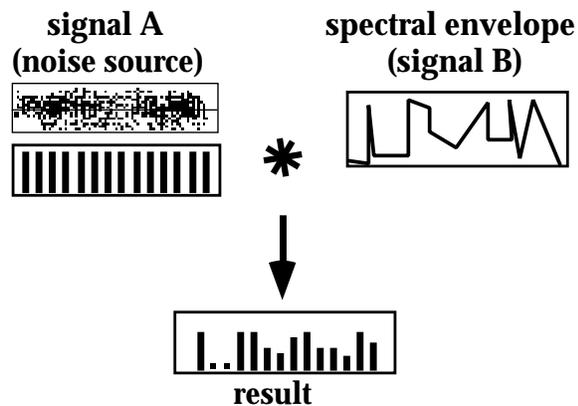


figure 3: subtractive synthesis

#### 3.2 Low dimensional control of complex spectral envelopes

The spectral envelope used in the above filtering application can also be obtained through signal analysis, in which case a second input signal, signal B, is needed. Signal B is analyzed for its spectral envelope, or amplitude spectrum, that describes how signal A will be filtered. Obtaining a spectral

envelope from an audio signal offers several interesting possibilities: spectral envelopes can be "collected" instead of being specified, and can change at a very fast rate (audio rate), offering a powerful method of dynamic filtering. Also, audio signals produced by standard signal processing modules such as a frequency modulation (FM) pair (one oscillator modulating the frequency of another) are of particular interest because they can produce rich, easily modified, smoothly and nonlinearly varying spectra [Chowning 1973] which can yield complex time varying spectral envelopes. These spectral envelopes can be modified using only 3 (FM) parameters: carrier frequency, modulator frequency, and modulation index. Likewise, other standard signal processing modules such as an amplitude modulation (AM) signal generator, an additive synthesis instrument, or a band-pass filter bank offer rich varying spectral information using relatively simple means with few control parameters. One of the advantages of using standard modules is that electronic musicians are familiar with them, and have a certain degree of control and understanding of their spectra.

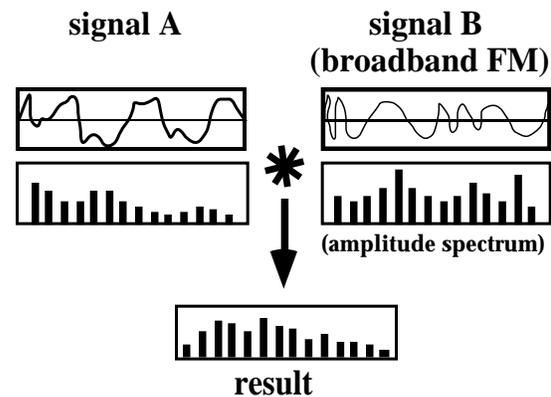


figure 4: dynamic filtering of signal A using the spectral envelope of signal B

#### 3.3 Cross synthesis

In this application two input signals are required: signal A's spectrum is convolved with the amplitude spectrum of signal B. Thus, the pitch/phase information of signal A and the time varying spectral envelope of signal B are combined to form the output signal. Favorable results are produced when Signal A has a relatively constant energy level and broadband spectrum, and when signal B has a well defined time varying spectral envelope. For example, when wishing to transform spoken or sung text, we assign the text material to signal B while specifying a pulse train, noise source or some other constant-energy broadband signal to signal A. Since the frequency information (pitch, harmonicity, noise content, etc.) of signal A is retained in the output, unusual effects can be produced when frequency

related changes occur in signal A. In the following example of a *vocoder*, text can be decoupled from the speaker or singer's "voice quality", allowing one to modify attributes of the voice such as noise content, inharmonicity, and inflection, independently of the text material.

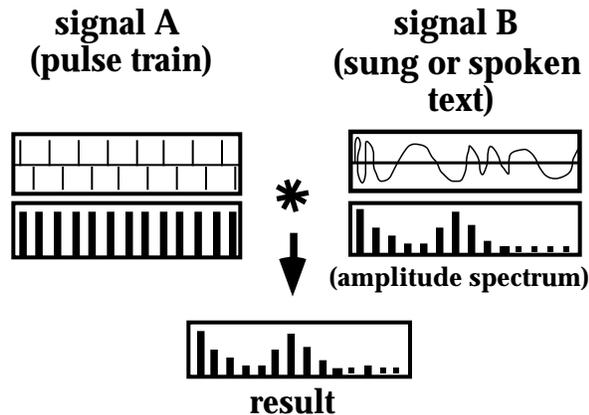


figure 5: cross synthesis

### 3.4 Mapping qualities of one signal to another

A simple FM pair may be used to provide an easily controlled, constant-energy broadband spectrum for use in cross synthesis as signal A. Musically, we have found that in some cases, the relationship between signal A and signal B can become much more unified if certain parameters of signal B are used to control signal A. In other words, real-time continuous control parameters can be derived from signal B and used to control signal A. For example, the pitch of signal B can be tracked and applied to signal A (FM) to control the two oscillators' frequencies. Envelope following of signal B can yield expressive information which can be used to control the intensity of frequency modulation (FM index) of signal A. In experiments incorporating the above, a mezzo soprano's voice was assigned to signal A, while her pitch and intensity were mapped onto signal B (FM), producing striking results akin to harmonization and frequency shifting.

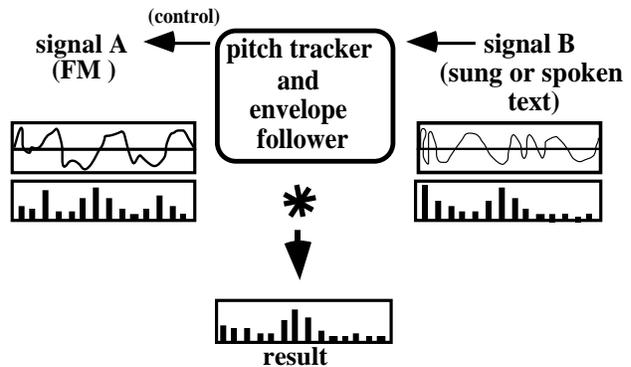


figure 6: cross synthesis using signals with linked parameters

Finally, it should be noted that interesting transformations can be produced by simply convolving signal A's spectrum with signal B's spectrum. In this case, the phase (frequency) and spectral envelope information from each signal figures in the output signal. Transformations of broadband sounds, akin to, but more pronounced than flanging, can be produced when convolved with the signal of a high index, inharmonically tuned FM pair, whose frequency parameters are controlled by the pitch of the first signal.

### 3.5 Frequency-dependent spatialization

In the spectral domain, the phases of a given signal's frequency components can be independently rotated in order to change the component's energy distribution in the real and imaginary part of the output signal. Since the real and imaginary parts of the IFFT's output can be assigned to separate output channels, which are in turn connected to different loud-speakers, it is possible to control a given frequency's energy level in each loud-speaker using phase rotation. The user interface of this application permits users to graphically or algorithmically specify the "panning" (phase offset) for up to 512 frequency components.

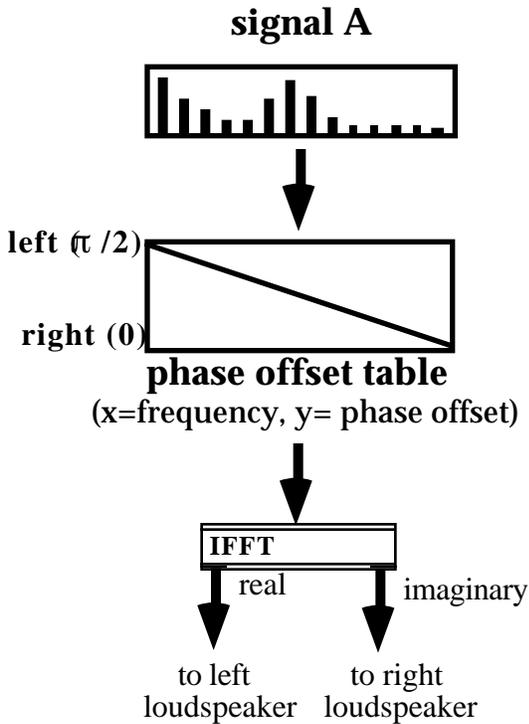


figure 7: Band-limited spatialization

### 3.6 Band-limited energy dependent noise-gate

In the spectral domain, the energy of a given signal's frequency components can be independently modified. Our noise reduction algorithm is based on a technique [Moorer & Berger, 1984] that allows independent amplitude gating threshold levels to be specified for up to 512 frequency band-limited regions of a given signal. With a user-defined transfer function, the energy in a given frequency range can be altered based on its intensity and a user-specified threshold level. This technique, besides being potentially useful for noise reduction, can be exaggerated in order to create unusual spectral transformations of input signals, resembling extreme chorusing effects. Using non-linear transfer functions, it is possible to modify the relative intensities of the input's frequency components, allowing for example, masked or less important components to be emphasized and brought to the aural foreground.

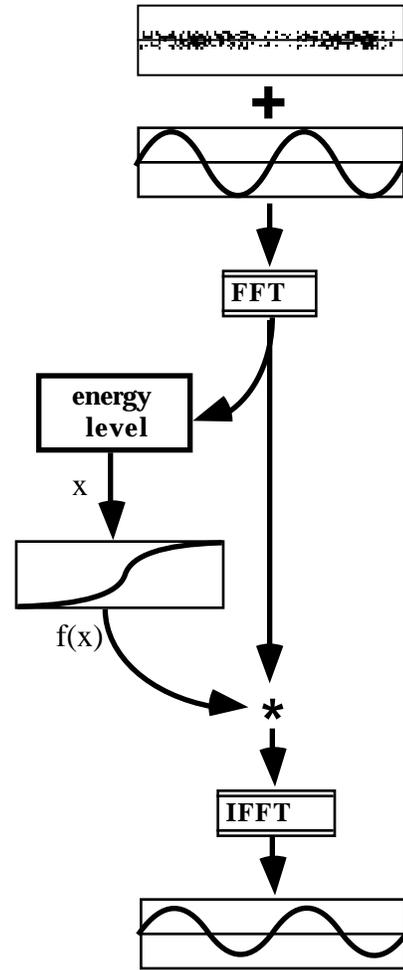


figure 8: Gating low amplitude noise

### 3.7 Band-limited frequency dependent noise-gate

Similar to the noise-gate described above, this module functions independently of gain; its output depends on the stability of the frequency components of the input signal. Using a technique borrowed from phase-vocoding [Gordon & 1987], time-varying frequency differences of components in a given band-limited region of the spectrum are used to determine the stability of those components. Pitched components in the input signal tend to be stable and can thus be independently boosted or attenuated.

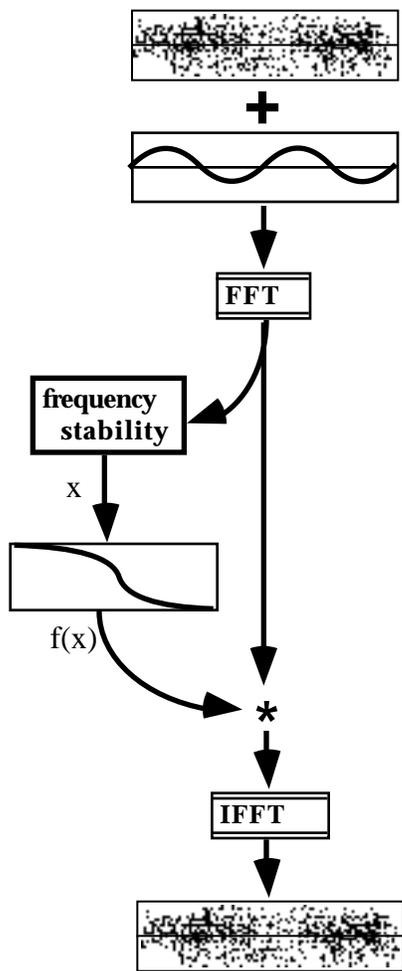


figure 9: gating stable frequency components

#### 4. Combining Processing Modules

The modules described above may be placed in series in order to perform multiple processing operations on a sound. Since most of the cost of processing occurs in time/frequency domain conversion (FFT and IFFT), modules operating in the frequency domain may be ganged together with great efficiency, requiring no additional steps of conversion.

##### 4.1 Dynamic range processing with graphic EQ

The 512 band filter module described above may be easily connected to another module, providing the additional possibility of high resolution filtering.

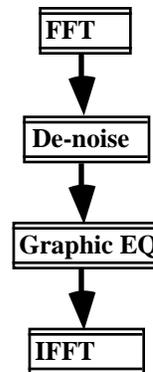
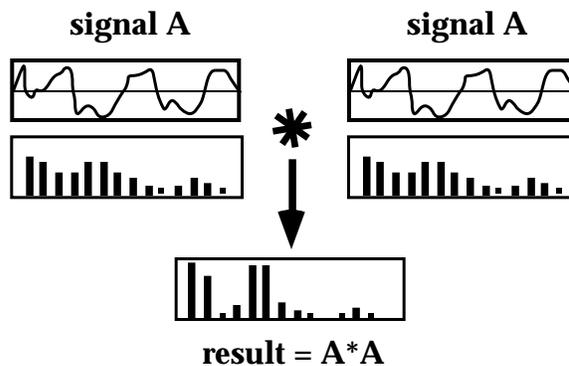


figure 10: signal flow for cascaded frequency domain modules

##### 4.2 Input scaling and additional control parameters for cross-synthesis

When two input signals of similar intensities and spectral distributions (eg.: two singers' voices) are convolved, the resulting spectral distribution can be quite different. In such a case, strong "low-mid-range" components can become much louder, while weaker higher frequency virtually disappear. For example, when convolving a signal by itself, the resulting energy of a given component is its square, as shown below:



By scaling the input or output signal(s), the "original" spectral distribution can be preserved. If in the above example, we take the square-root of the output signal, a given component's energy is now the arithmetic mean of the energy of its input signals, and not the square. In this case we recover the original input signal.

$$\text{result} = \text{sqrt}(A*A) = A$$

The algorithms for cross-synthesis shown above can be expanded to include additional processing units, that allow for scaling and provide more control parameters. A compressor/expander based on the energy dependent noise-gate mentioned earlier is

applied to one of the two input signals before convolution. The choice of compression/expansion functions determines the way the energy in the output signal will be scaled; certain choices (such as a square root function) help preserve the spectral distribution of the input signals. Thus, two input signals of similar intensities and spectral distributions will combine to form a spectrum whose components' relative energies remain little changed.

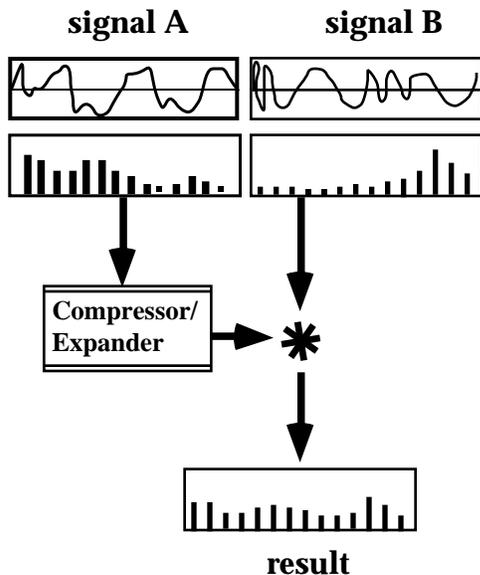


figure 11: energy scaling to preserve spectral distribution

By choosing a compression/expansion function that boosts or cuts the energy of weaker components in one of the input signals, the degree of spectral intersection of the two inputs can be specified. The compression/expansion ratio parameter (or intensity of compression/expansion) provides dynamic control over the "degree of spectral intersection" of the two input signals. This parameter is particularly useful when cross-synthesizing dissimilar sounds such as voice and percussion.

## 5. Future Directions

Useful techniques for sound manipulation in the frequency domain are proposed by the phase vocoder [Dolson 1986; Nieberle & Warstat 1992]. The authors are currently working on alternative methods of sampling and granular synthesis that operate in this domain, based on real-time phase vocoding [van der Heide, 1994]. At present we are able to modify a sound's spectrum and duration independently, and are working towards being able to perform pitch transposition independently of the spectral envelope

(formant structure), thus allowing one to change the pitch of a sound without seriously altering its timbral quality. Additionally, we are exploring techniques for smooth sample looping and cross-fading between sounds.

## 6. Summary

With the arrival of the real-time FFT/IFFT in flexible, relatively general, and easily programmable DSP/control environments such as Max, non-engineers may begin to explore new possibilities in signal processing. Though our work is still at an initial stage, we have gained some valuable practical experience in manipulating sounds in the spectral domain. Real-time convolution can be quite straightforward and is a powerful tool for transforming sounds. The flexibility with which spectral transformations can be done is appealing. Our DSP configuration is fairly simple, and changes to its topology and parameters can be made quickly. Control signals resulting from detection and tracking of musical parameters offer composers and performers a rich palette of possibilities lending themselves equally well to studio and live performance applications.

## Acknowledgements

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