# A Roughness Model in Pd for an Adaptive Tuning Patch Controlled by Antennas

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## ABSTRACT

This paper describes a patch implemented in puredata that is centrally based on the Adaptive Tuning concept. Roughness values of musical intervals are plotted into a curve graph according to a roughness model developed by the authors. Minimum and maximum values of the curve are then used as scale steps of this spectrum's tuning for the Adaptive Tuning modules, which are controlled by Antenna Sensors.

## Keywords

Roughness Model, Adaptive Tuning, Theremin, Interaction.

## 1. INTRODUCTION

The theremin, one of the earliest fully electronic musical instruments, is based on the concept of proximity sensors (antennas) that control pitch and volume, enabling it to be played without being touched. Because it is still a rather unusual musical instrument, its intonation technique remains particularly difficult – mainly because it has a continuous control without any visual marks. These features explain why the theremin is used mostly for eerie glissando sounds and vibrato like gestures (as in some sci-fi movie sound FXs). Theremins are not available on every musical instrument store, but nowadays it's easy to find several theremin diagrams for one to build it and also circuits for sale on internet sites such as www.thereminworld.com.

The theremin's sound generating circuits are still quite modest compared to the latest synthesizers, this is because the instrument retains the original sonority of early electronic sounds by the time it was conceived. There are some MIDI theremins that also can control other synthesizers, this means they provide new sound possibilities but also that they are even rarer. Nevertheless, some synthesizers own a similar proximity sensor procedure (usually obtained by light sensors) to control some synthesis parameters.

In a similar fashion, proximity sensors can be connected directly to the computer in order to control several parameters of sound designed in a computational environment. For that, the development of antenna sensors (as a good simplification of the original theremin diagram circuitry) was pursued to provide the ability of controlling a diverse set of sounds as well as different parameters in puredata.



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In our patch, we needed a controller that would provide a highly continuous data to the Adaptive Tuning concept. Hence, the antenna sensors were a great fit and were used in the patch to control the pitch as the traditional theremin. Unlike the traditional theremin, though, the Adaptive Tuning concept allows the theremin's control of pitch to be adjusted in real-time according to a scale.

The unusual intonation technique of the theremin can then be overcome by the concept of the Adaptive Tuning presented here, which can alter the pitch data automatically according to a specified tuning. Nevertheless, we have been exploring the antenna sensors not automatically for our musical purposes.

The scales used in the adaptive tuning patch can be derived by a sound's spectrum via a psychoacoustic roughness model previously developed by the authors. The roughness model and its background in psychoacoustics are presented on the next section of this paper. Section 3 describes the patch implemented in puredata and its features, this is where we explain how a scale is generated by the roughness model, how the concept of Adaptive tuning is explored and also how the antenna proximity sensors control it. Section 4 presents some final discussions and projections of the research.

Previous publications by the authors [11-14] have been discussing the roughness model in puredata and its applications. The work reported here is part of a master's research in *Creative Processes* at the Music Department of UNICAMP (State University of Campinas – São Paulo – Brasil), which is being developed at NICS (Nucleus of Interdisciplinary Sound Communication). The research and development of technological tools presented here are still in development and have been applied in the analysis of the relation between tuning and spectrum [11-12] as well as on some creative applications [13]. The research project concerns the creation of music with alternate tunings. For that matter, the research departs from Perception and Psychoacoustic studies to understand some aspects of the resources concerning microtonal or alternative tuning systems.

## 2. THE ROUGHNESS MODEL IN PUREDATA

The auditory sensation of slow amplitude fluctuations is called "beatings", and they can occur by two sine wave's constructive and destructive interaction. The sensation of "roughness" happens when the tax of these fluctuations are over 20 Hz up to an interval that depends on the Critical Bandwidth. Roughness sensation tends to be "unpleasant" to the ear in western culture, so it was elected as the main element of Sensory Dissonance – a psychoacoustic concept of dissonance focused on its sensorial aspects.

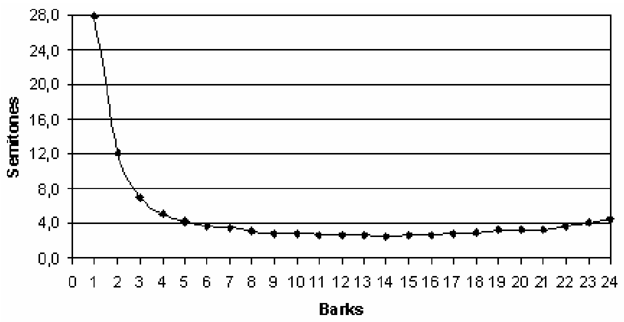


Figure 1) Non linear Relation Between Barks (X) and Equal Tempered Semitones (Y) – Graph's Data From [2]

Plomp & Levelt's work [1] affirms that the sensation of roughness is related to the Critical Bandwidth as measured by Zwicker [2]. Zwicker's Critical Band scale unit is named *Bark*[1] and there are 24 Barks throughout the whole auditory pitch range (thus 0 to 24 barks comprises the range from 20 Hz to 20 Khz). The size of Critical Bands are not proportional to the logarithmic scale of pitch (equal temperament) or the scale in Hertz. Figure 1 shows the size of Critical Bands in Equal Tempered Semitones.

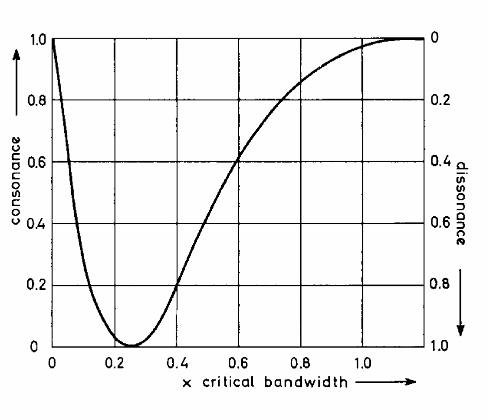


Figure 2) Consonance/Dissonance Curve of Equally Loud Pure Tones in the Range of a Critical Bandwidth – As Published in [1]

According to the psychoacoustical measurement of Plomp & Levelt [1], the interval difference that gives the maximum Sensory Dissonance for equally loud pure tones corresponds to about one fourth of the Critical Bandwidth. Figure 2 is the Curve[2] of Plomp & Levelt's mean results in the span of about a Critical Band and represents each of the 24 Critical Bands over the whole auditory pitch range. The Curve in Figure 2 decreases in consonance as the interval increases from unison (0 bark) to one fourth of the critical bandwidth (0.25 bark), and it rises afterwards until it reaches a minimum dissonance value when the interval is about 1.2 barks.

Based on their results from Figure 2, Plomp & Levelt [1] also calculated the roughness of complex tones by summing the roughness values of every pair of sine tones contained in the spectrum. Figure 3 shows a Curve represented in Hertz (register of about an octave) between two harmonic complex tones with six equally loud partials. In Figure 3, minimum Sensory Dissonance occurs when partials align – thus eliminating the sensation of beatings and roughness. This is especially true for the unison [1:1] and octave [2:1], where maximum alignment/Sensory Consonance occurs.

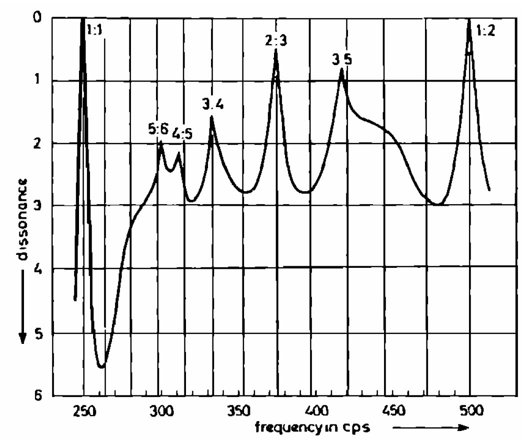


Figure 3) A Harmonic Spectrum's Curve – As Published in [1]

Plomp & Levelt's mean results are plotted in Figure 2, which is the basis of several roughness models like Sethares' [3] – the model we adopted as our starting point. Sethares [3] formulated a parameterization of Plomp & Levelt's curve to return roughness values for pure tone intervals in barks, in the same way as the horizontal dimension of Figure 2. Sethares' [3] model calculates the roughness values of complex tones from a list of frequencies and their relative amplitudes. Sethares' implementation of his model in *Matlab* [3] is also published on the internet[3], and was translated to puredata as the first step of our research. We then also included a different approximation of Plomp & Levelt's curve as defined by Parncutt[4] [4]. Sethares' formula [3] was normalized (by a factor of 5.56309 as in Figure 5) to return a maximum arbitrary value equal to 1 like Parncutt's [4].

Figure 4 shows a subpatch named "HzToCbrz" that provides five different conversion functions from Hertz to Barks tested in our research. This is useful because a sound spectrum's frequency list is usually provided in Hertz, and we need the values in the Bark scale [2] to access the roughness values from both approximations [3-4] of Plomp & Levelt's Curve (Figure 2). This subpatch was utilized for both Sethares' [3] and Parcutt's [4] approximation of Plomp & Levelt's Curve. But actually, Sethares' Matlab code [3] originally implements a different approximation formula of his, which contains another procedure to conveniently account the nonlinearity of the bark scale in relation to Hertz. We discarded his procedure because it wasn't as accurate as the other functions

[1] As a homage to Heinrich Georg Barkhausen, the german physicist who discovered the Barkhausen effect and also worked with loudness measurements (used to determine the length of critical bands).

[2] The Consonance/Dissonance Curves on this paper represent the roughness values (vertical dimension) of frequency difference in relation to a fixed base tone (horizontal dimension).

[3] At <http://eceserv0.ece.wisc.edu/~sethares/comprog.html>.

[4] Who worked on another roughness model [5].

we have researched and used his formula in the original parameterization [3].

"HzToCbrz" is one of several subpatches regarding psychoacoustical conversions that were studied during our research and will be distributed in the form of a puredata library. The function that best approximates the relation between Hertz and Barks is actually a combination of two formulas[5] as advised by Clarence Barlow in personal correspondence[6]. Apart from the procedures that approximate Plomp & Levelt's Curve and the conversion from Hertz to Bark, our model implements the work of Vassilakis [6] on relative amplitude weightning – because Plomp & Levelt's model [1] only accounts equally loud partials.

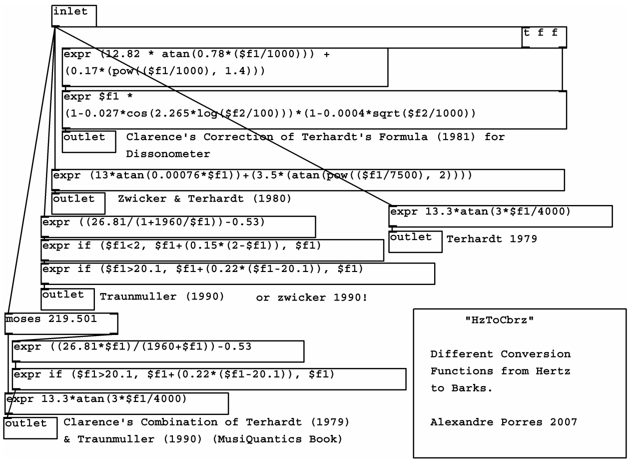


Figure 4) Subpatch with Five Conversion Functions from Hz to Barks

Vassilakis [6] provides a convenient way of weightning roughness values concerning the degree of amplitude fluctuation[7]. But another key element that accounts the influence of amplitude perception is the Fletcher & Munson [7] Equal-Loudness Contours, provided to us in the form of a lookup table by Clarence Barlow – who had implemented it in his roughness model [8]. Barlow currently adopts a conversion function of his own, which can be implemented by us in the future in order to replace the Equal-Loudness Contours' lookup table.

The loudness values of this lookup table is consulted by the crossing of *X* dimension (frequency value in Midicents) and *Y* dimension (amplitude value in dB). The conversion between relative amplitude values from our amplitude list to dB can be done via puredata's native objects *rmstodb*/*dbtorms*, just as frequency values in Hz to Midicents can also be easily converted via *ftom*. Figure 5 shows the implementation in puredata of Plomp & Levelt's approximation functions [3-4] as well as Vassilakis' [6] roughness weightning function.

[5] Use Terhardt's formula [9] for values below 219.5 Hz, and Traunmüller's [10] for values above. This is the outcome of HzToCbrz's leftmost outlet.

[6] Check Clarence's work on his forthcoming book 'Musiquantics'.

[7] His function was also normalized (by a factor of 2 as in Figure 5) to return a maximum arbitrary value equal to 1 when the relative amplitudes are at a amaximum of 1 (also arbitrary).

In this way, for a pair of sine tone frequencies (f1-f2) and their relative amplitudes (A1-A2), the model returns a Roughness Value (R) according to the diagram flux presented in Figure 6. Like Plomp & Levelt's model [1], to account the roughness of complex sounds, the model adds the roughness values of every combination of sine tone components of the spectrum. The model is responsible for generating Dissonance Curves, discussed on the next section.

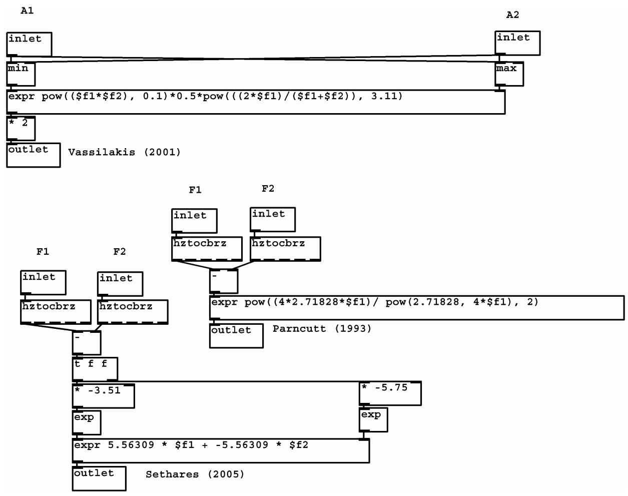


Figure 5) From up to Below, the Implementation of Vassilakis' [6] Parncutt's [4] and Sethares' [3] Formulas

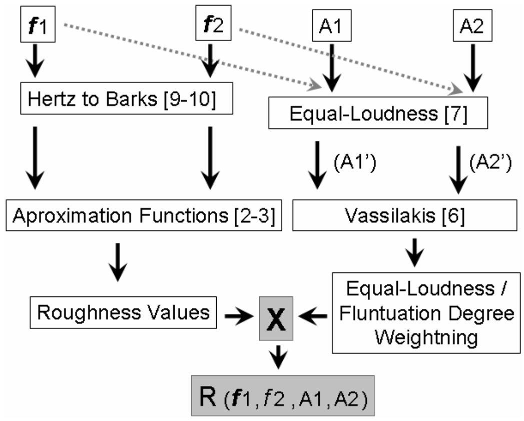


Figure 6) Diagram Flux of the Roughness Model

## 3. THE PATCH

The patch has two different procedures for sound generation: The Additive & Wavetable Synthesis. Both can provide sound spectrum's lists, which are used to plot Dissonance Curves via our roughness model. From the Dissonance Curves we can derive a musical scale that is sent to the Adaptive Tuning section of the patch. There are two Adapting Tuning models which can be controlled by antennas as described on this section.

### 3.1 Sound Synthesis & Wavetable

Figure 7 presents the additive synthesis section of the puredata patch we developed, as well as other features. This section includes 32 oscillators in parallel. A frequency list in harmonic relation to a fundamental frequency is created automatically from a relative amplitude list. For example, inside the

"Get_the_WaveForm_And_Do_The_FrequencyList" abstraction, a list of amplitudes [1, 1, 1] and a fundamental partial of 100Hz creates the following frequency list: [100hz, 200hz, 300hz]. In this way, some amplitude lists are stored as presets for classical waveforms such as square, saw and triangle – since they are all harmonic spectrums that differ only in their relative amplitude list. Such waveforms could be related to early electronics sounds from original theremins.

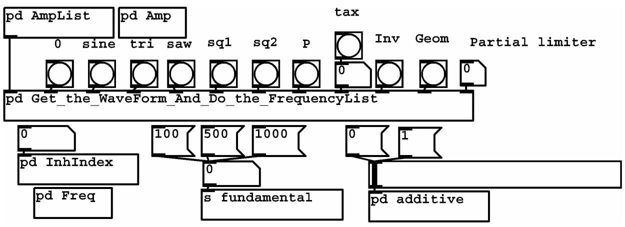


Figure 7) Additive Synthesis Section of the Patch

One can, for example, choose a square wave preset that will generate 32 harmonic partials, and also limit the partial content from 1 to 32 (using the partial limiter number box). Another feature is to insert an inharmonic index to control spectral compressing (negative) or stretching (positive). It is also possible to generate partials not in harmonic relation, but in geometric and arithmetic relation[8].

"Pd Freq" & "Pd Amp" abstractions provide fine tune control of the 32 oscillators frequency and amplitude via MIDI controls. Custom frequency and amplitude lists can also be set by hand. Actually, any frequency list (up to a maximum length of 32) can be withdrawn from a FFT analysis.

As to the recorded samples in wavetable loops, the partial limit depends on puredata itself. The synthesizer and wavetable loops are independent and pre-processed; they do not belong to the real time process. This pre-processed stage regards the development of a sound database and their corresponding scales derived by Dissonance Curves.

## 3.2 Dissonance Curve

In the patch, either synthesis or samples in wavetables can be used. The spectrum of sounds is represented by a list of frequencies in Hertz and another list with their respective relative amplitudes (from zero to one). This information is taken directly from the oscillators if the sound is synthesized or by a FFT analysis if the sound is a chosen sample. The spectrum lists are then doubled and an increasing interval spacing between the two spectrums is performed by an algorithm. This means that the sound spectrum analyzed by the roughness model in the Dissonance Curve plot is actually the sum of two tones with the same spectral content in different intervals.

In our patch, the Curves are derived from a fixed tone in Hertz, which is the same as the first partial of the spectrum's frequency list. The register of the varying tone (as well as the register of the curve) can be set in semitones and cents[9] (upwards, downwards, or both). The resolution of the varying tone intervals can also be changed and it's usually set as one cent. The plots are similar to the Figures 2 and 3, only they are inverted and displayed in the logarithmic scale of semitone intervals.

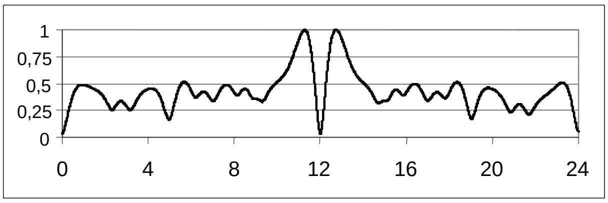


Figure 8) A Dissonance Curve Derived by the Roughness Model

Figure 8 shows the Dissonance Curve our patch plotted for a triangle wave form containing 7 partials – X is Semitones and Y is Relative Roughness. The fixed tone is 440hz (in the middle of the plot), this two octave range Dissonance Curve is from 220hz to 880hz – one octave upwards and downwards 440hz.

## 3.3 Deriving Scale from Dissonance Curve

Intervals in just intonation correspond to integer ratios as in the harmonic series. Sound spectrums that are harmonic do not produce much beatings or roughness in just intonation – because some of the partials align in such intervals. This can be confirmed by the roughness model, where minimum Roughness/Sensory Dissonance values correspond to just intonation intervals for harmonic spectrums [11-12].

Hermode tuning provides a model to calculate and adjust musical intervals according to just intonation. It can also be used in real-time to tune a synthesizer, see (http://www.hermode.de). But this approach does not work for inharmonic sound spectrums, in which partials align in corresponding inharmonic intervals, hence, promoting roughness in just intonation[10].

Sethares [3] also developed an adaptive tuning system in MAX/MSP with scales derived by Dissonance Curves. In his patch, adaptation occurs according to minimum values of Dissonance Curves at a specified time schedule or automatically. Sethares' patch and programming routines were not used (or even tested) as the starting point for our patch. Only the same concept was adopted to develop a similar approach starting by scratch.

The information used to generate scales in the puredata patch is provided by valleys (consonant intervals) and peaks (dissonant intervals) from the Dissonance Curve of a specified spectrum[11]. Figure 9 shows a Dissonance Curve plot generated in our patch, as well as the scale steps of its minimum and maximum values. A peak in the plot represents a high sensorial dissonance value, and a consonance is represented by a valley. Figure 9 represents sensorial dissonance in the vertical axis and semitone steps in the horizontal axis, this is the scale derivation of a slightly inharmonic sound spectrum (note the last valley just above an octave). Figure 9 is actually a screenshot of one of the patch's table that shows you the derived scale, which is represented by the lines over the Dissonance Curve.

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[8] This is a rather unusual procedure, adopted here to generate an unusual inharmonic context.

[9] 1 cent = 1/100 of a equally tempered semitone.

[10] In fact, musical instruments do not produce theoretically perfect harmonic spectrums. Thus, Just Intonation is a theoretical model that can only be validated by static electronic (and musically not that interesting) sounds.

[11] This approach is a bit different than Sethares'. His scale derivation is only based on valleys (consonant intervals).

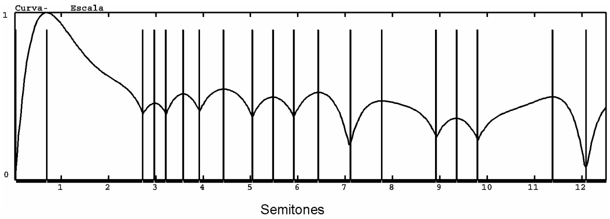


Figure 9) Dissonance Curve Plot and the Derived Scale

So far, we have been reporting a pre-process that does not belong to the real-time interaction. This first stage regards the collection of information that can be stored and sent to the adaptive tuning modules.

## 3.4 Adaptive Tuning & Antenna Control

As mentioned above, the antenna sensors provide input data for pitch. As the user improvises around the antenna and sustains a particular pitch, the adaptive patch can change the tuning automatically in real time, on a specified time in seconds, or even at a specified speed (interval in cents per second). The system's parameters for adaptive reaction are: a) the nearest step in the scale, b) the nearest valley (maximum consonance) step in the scale or c) nearest peak (maximum dissonance) step in the scale.

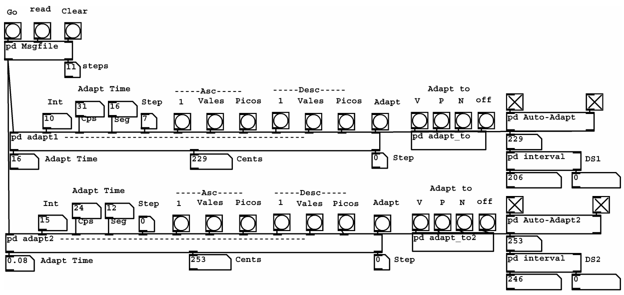

Figure 10) Two Adaptive Tuning Modules

The antenna sensors were connected to the computer via the arduino board[12] and each antenna controls one voice of the patch; two voices are connected each to an adaptive tuning module (see Figure 10) that adapts its tuning basing its interval relation to a third fundamental voice from the synthesis section (this voice can also be controlled by an antenna). Figure 11 presents the diagram that illustrates the concept of the patch concerning the previous items of this paper: Sound Synthesis & Wavetable, Dissonance Curve Plot & Scale Derivation (by means of the roughness model), Adaptive Tuning & Antenna Control.

Several sensor circuitries were studied. We are currently working on the enhancement of the circuits provided by Andrei Smirnov[13]. We have also been developing a frequency to tension converter that can connect any theremin to the arduino board from its audio output. Further research shall promote an enhancement of the sensors that are, for the moment, satisfactory. Other applications of such sensors are being considered, not only connected to the Adaptive Tuning patch concept.

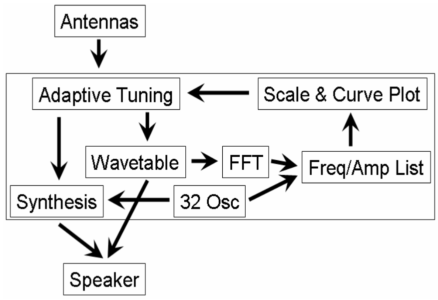


Figure 11) Diagram of the Pd Patch

## 4. DISCUSSION & CONCLUSION

The roughness model we developed was used to generate scales based on peaks and valleys (maximum consonance and dissonance steps) for an adaptive tuning module. A further intent is to enhance the model by including the masking effects. Until now, the system has proven to be successful regarding the purpose of scale generation of relative simple sound spectrums.

The model is still incipient for the Dissonance Curve's analysis of dynamic and complex sounds (as is the case of real musical instruments). We found that more than 32 partials start to consume a great deal of computational time, not to mention that a dynamic sound should be analyzed regarding its variation in time, which implies on a three dimensional dissonance graph. Real instruments also vary considerably their spectral distribution depending on performance nuances, and formant frequencies contribute to a slight different spectrum content according to the register. Thus, there is still a lot of work to be done in the Dissonance Curve analysis of musical instruments.

The roughness model also has other analysis applications, like the analysis of digital sounds in time. This discards the Dissonance Curve plot and focuses on the roughness value of a specified FFT window. Hence, a bigger list of partials might be used without compromising that much of computational time.

Parncutt's formula [4] is a closer approximation of Plomp & Levelt's Curve[14] (from Figure 2) than Sethares' [3]. But this discussion brings the attention to how accurate and important the work of Plomp & Levelt [1] actually is. Their work is a consolidated classic in the psychoacoustic literature. Nevertheless, more up to date research could be done in this area. As for the scale generation matter in our patch, Sethares' approximation actually provides a better peak and valley detection. Thus, it is best to generate scales without actually compromising the roughness model (more details in [14].

Pressnitzer & Gnansia [15] developed another roughness model in puredata[15] that adopts a different time-frequency analysis methodology. According to Pressnitzer & Adams [16], there is a dependence of roughness on phase effects, which is not implemented in our model. On the other hand, Vassilakis states[16]

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[12] Arduino <http://www.arduino.cc/> is an open-source physical computing platform based on a simple I/O board that can take several inputs from switches and sensors. It can also be easily connected to Puredata patches as a control input.

[13] Check his circuitries at the theremin center website <http://asmir.theremin.ru/tsensors_sch.htm>.

[14] The work of Clarence (still in progress) shows this clearly.

[15] Available at <http://cognition.ens.fr/Audition/tools/realtime>.

[16] At <http://musicalgorithms.ewu.edu/learnmoresra/moremodel.html>.

that the absence of the phase parameter in his model[17] does not significantly distort the model's calculations.

The patch described on this paper has its own idiomatic musical features, some experiments with it were developed using wavetables from stringed instruments' harmonics (violin and viola). As the spectrum content of these wavetables are quite simple, combining these sounds sort of resembles the idea of additive synthesis[18]. An expressive idiomatic feature of the patch is the combination of sounds as a mean to generate complex sound textures: a dynamic sound motion flowing towards dissonant or consonant peaks and valleys, and not to create chords as the Hermode tool.

The system provides a simplified and generic use of the theremin in which a musician plays any sound using the computer as a dynamic sound generator. It also re-tunes the theremin to desired scale steps, which can be used in real-time to facilitate the intonation technique. The study reported here reflects a broader research related to a Master's degree program at NICS/UNICAMP. More information about the research as well as the patch, its manual, the dissertation, music, etc… can be found at: <http://www.nics.unicamp.br/atual/pessoal_porres.html>[19].

# 5. ACKNOWLEDGMENTS

Thanks to FAPESP that financially supports Porres on his Masters' program and the Brazilian Agency CNPq that financially supports Manzolli, his supervisor. Sethares and Vassilakis were very open and helpful in private correspondence by e-mail regarding the roughness model issues. A special thank must be sent to the composer Clarence Barlow who is also developing research in this area and was an important collaborator as he provided some hints, clues, and questionings that served as inspiration and guidance. Barlow also provided some codes and a look-up table for the Equal-Loudness Contours he had transcribed by hand! In fact, the roughness model here is almost an implementation of his model [8], only mixed with Sethares' algorithm [3] and differed by the inclusion of Vassilakis' work [6]. The research partner from NICS Fábio Furlanete was a great helper by solving some technical puredata problems, not to mention the work he had translating Sethares' Matlab code into puredata (the big push that made this work take off).

The colleagues and composers Alexandre Fenerich, Giuliano Obici who work with the arduino board, as well as Renato Uchôa who is also an expert on Voltage Control. Andrei Smirnov was extremely helpful explaining about how his sensors work and also provided some assistance as well as arduino programming routines. The electrical engineering doctorate student Pedro Oliveira and his supervisor Prof. Dr. Bassani are contributing to the enhancement and development of the antenna sensors at CEB (Biomedical Engineering Center/UNICAMP), and Renato Brandão was the electronic technician who manufactured some of the circuitries.

[17] His online roughness tool [17] is available on the net at <http://musicalgorithms.ewu.edu/algorithms/Roughness.html>.

[18] A piece for string players was conceived and reported in [13].

[19] If the link does not work, please look for Alexandre Torres Porres at NICS' website <http://www.nics.unicamp.br> or e-mail the authors.

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