ON THE PLAYING OF MONODIC PITCH IN DIGITAL MUSIC INSTRUMENTS

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ABSTRACT

This paper addresses the issue of controlling monodic pitch in digital musical instruments (DMIs), with a focus on instruments for which the pitch needs to be played with accuracy. Indeed, in many cultures, music is based on discrete sets of ordered notes called scales, so the need to control pitch has a predominant role in acoustical instruments as well as in most of the DMIs. But the freedom of parameter mapping allowed by computers, as well as the wide range of interfaces, opens a large variety of strategies to control pitch in the DMIs. Without pretending to be exhaustive, our paper aims to draw up a general overview of this subject. It includes: 1) a review of interfaces to produce discrete and/or continuous pitch 2) a review of DMI maker strategies to help the performer for controlling easily and accurately the pitch 3) some developments from the authors concerning interfaces and mapping strategies for continuous pitch control 4) some comparisons with acoustical instruments. At last, a Max/MSP patch –publically available– is provided to support the discussion by allowing the reader to test some of the pitch control strategies reviewed in this paper.

1. INTRODUCTION

Opposition between continuous and discrete is a question which, beyond the universe of music, has occurred throughout the history of sciences and philosophy since antiquity. It overlaps sometimes another dualism, which is usually established between categorical and quantitative. In the musical field, quantification of pitch values and duration on scales or grids is omnipresent. Western music notation acts as a clear evidence of this categorization.

Nevertheless, many instruments, such as string instrument or vocal music, allow to glide continuously from one pitch to another. New electronic instruments from the XX$^{\text{th}}$ century like Theremin and Onde Martenot [1], also offered the musician the possibility to play glissandi. Moreover, some composers [2] drew non-scaled soundscapes that explored large frequency ranges through continuous sweeps. Iannis Xenakis' Metastasis, created in 1955 at Donaueschingen festival, stands among the most significant works that arised from this research.

The concept of pitch, and the theories on harmony brought up with it, is a vast field of study. This article focuses on playing techniques, that allow to control precisely the pitch on a digital music instrument (DMI). As developers and players of such musical instruments, we will take here a closer look at the interfaces and algorithms meant for continuous control of pitch. This article will aim at reviewing existing techniques as well as introduce techniques developed by the authors. We also provide a simple implementation[1] and organisation of these algorithms in the Max programming language[2], as a cookbook for musician and digital instrument makers.

2. PERCEPTION AND PRODUCTION OF PITCH

2.1 Pitch perception

The auditory system allows to distinguish very small pitch variations. In the case of synthetic singing vowels with a fundamental frequency of 80 Hz and 120 Hz, the smallest discrete perceptible shift of pitch ranges between 5 and 9 cents. Common sense tends to link pitch to the fundamental frequency of an harmonic sound, but pitch perception is not a thing as trivial as one could first imagine. Psychoacoustics showed how much this perception is contextually and culturally biased. A known example is the perception of pitch on low-tessitura instruments, such as the contrabassoon, which melody of certain overtones is sometimes more likely to be perceived as the fundamental pitch than the fundamental frequency of the notes played [4]. Meanwhile, some instruments make a purposeful use of their rich timbre to enhance specific harmonics and produce a melody in the high range (didgeridoo, jaw harp, overtone singing).

Timbre can also disturb the recognition of a predominant pitch. For example, instruments with non-linear vibrations, such as bells, show several non-harmonic frequencies. Some drums also do not have a clearly perceptible fundamental frequency, when their sound is made

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[1] Patcher *LAM.pitch.processing.maxpat* from the LAM-lib available at `https://github.com/LAM-IJLRA/lam-lib/tree/master/examples`

[2] Max ©Cycling'74 - `http://cycling74.com/`

of a broad spectral hump or when their fundamental frequency evolves rapidly in time. Pitch perception relies on two concurrent auditory mechanisms. The terms "autocorrelation" and "pattern-matching" tend to replace the terms "temporal coding" and "place coding" to describe these two auditory mechanisms [5] which help us identify a pitch, but these modes of perception interweave constantly, as Shepard [6] and Risset showed with the famous endless glissando[3].

2.2 Pitch production in acoustic instruments

Pitch is an essential component of music; it is why harmonicity is so important in the instrument making process. The production of a salient harmonic sound is most often due to a resonance phenomenon, that filters out most frequencies other than the fundamental harmonics (that, is not always the case in the digital field, as will be seen here below). Different pitches can then be obtained:

- by playing on several elements tuned differently (e.g. harp strings, marimba bars, etc.);
- by modifying the structural characteristics of a resonant body, mostly its length (e.g. tube of wind instruments, cello strings, etc.);
- by selecting precise harmonics in a rich sound (e.g. didgeridoo, diphonic singing, harmonics on a guitar string).

These techniques can be used simultaneously, e.g. when modulating the pitch around an average value. For instance, the player can modulate the tension of a string to modify slightly the pitch, while using another string to change the pitch more clearly. Among wind instruments with a mouthpiece, musicians can have a specific control on the vibration of their lips or the reed to slightly modify the pitch whereas they modify the length of the air column by changing the number of obstructed holes.

2.3 Pitch production in digital instruments

With digital instruments, the sound field is produced by the loudspeaker (or any other acoustic transducer), when excited by an audio signal. The pitch of this audio signal can result from any or several of these processes:

- the playing speed of a wavetable (additive, sample based, granular, FM synthesis...);
- the content of the wavetable itself;
- a delayed feedback that induces a resonant filter (subtractive synthesis, karplus-strong...);
- a frequency domain [re]synthesis (FFT).

The salient frequencies are thus no longer tied to the body of the acoustic instrument. The "symbolic" pitch (that one can compare to the pitch written in scores) becomes a digital variable that can be manipulated by algorithms, hence giving more freedom in the production of a tuned sound signal.

3. PLAYING INTERFACES

Most of the acoustic instruments let the musician play on a discrete scale, with the help of keys, bars or frets causing them to vibrate at specific frequencies defined during manufacturing and tuning. Some of them allow to produce large glissandi, as is the case for the cello, the trombone, or —to a lesser extent— wind instruments like bansuri flute, with appropriate playing techniques. In some cases, accessories may also help to overcome the discrete scale of a music instrument (e.g. bottleneck for the guitar). Last, a few mechanical automaton, such as music-boxes or barrel organs (however they may not be included in so-called music instrument, most of time) allow to play pitched notes by using pre-composed material, usually with discrete pitches. The next sections will present how this lutherie can be transposed in the digital world.

3.1 Specificities of digital music instruments

Digital music instruments are very recent in music history and possess their very own specificities [7].

Some of these characteristics are shared with electronic instruments: energetic decoupling between the instrumentalist's gesture and the produced sound; spatial decoupling (the sounds are produced by loudspeakers, possibly away from the musician); modularity of hardware interfaces and audio processing (on modular synthetizers).

Some others are new [8]: decoupling due to symbolic encoding; embodiement of (very fast) computation; embodiement of (large amount of) memory; evolving nature of softwares, allowing a more radical modularity; etc.

3.2 Interfaces for discrete pitch

3.2.1 Keyboard and fretting

Except for the instruments that strongly resort to harmonic modes such as brass, the disposition of pitches on acoustic instruments is usually arranged according to a scale. The piano keyboard allows to play all pitches from the chromatic scale, but is organised around the C major diatonic scale. If this layout is not the most ergonomic one, the fame of this instrument led to use it as the standard pitch layout for the first synthesizers.

Other pitch layout have been proposed. In particular, so called "isomorphic" keyboards inspired by Euler's Tonnetz, like the harmonic table or the Wicki-Hayden system (Figure 1), propose a different layout for the pitches, which allow to retain the same interval pattern independently of any transposition. We are seeing a renewed interest for this kind of keyboard [9] and several instrument manufacturers adopted it for their devices (Ableton Push[4], Thummer[5], Dualo[6], etc.).

Implementing these topologies from a 2d continuous surface is pretty straight forward, as it is defined by 2 vectors generating a mesh. For instance, the Wicki-Hayden layout can be generated by the simple equation $pitch = 2x + 7y$, where x and y represent the 2 axes shifting the pitch by

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[3] See `http://en.wikipedia.org/wiki/Shepard_tone` for details.

[4] `https://www.ableton.com/en/push/`

[5] `http://www.thummer.com/`

[6] `http://dualo.org/`

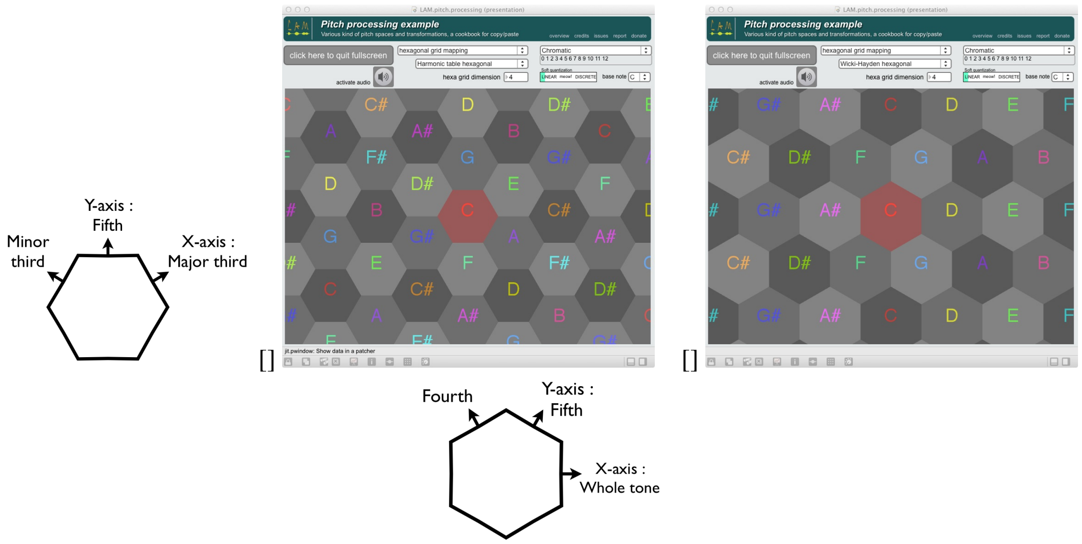

Figure 1: (a) Harmonic table and (b) Wicki-Hayden note layouts, both implemented in the LAM-lib.

a whole tone and a fifth, respectively. Our software implementation makes it possible to use such notes layout in an interchangeable way, using continuous surfaces such as graphics tablets and multi-touch surfaces.

3.2.2 Incremental keyboard / sequencers

A few instruments have been created with the goal of playing relative pitches rather than absolute pitches. The Samchilian[7] is such an instrument, which keyboard aims at playing pitch intervals rather than the pitch values. Despite the interest of this type of keyboard for producing melodies and arpeggi, it has neither become very popular to this day, nor did the instrument reach a stable form so far.

A sequencer contains a score of events, usually notes defined by their pitch, intensity and length. While the sequencer is best known as a “play/stop” machine, an instrumental way to play a sequence, considered as a succession of musical events ordered in time, has been investigated by a few people. Among them, Jean Haury led a long research comprising study, implementation, and virtuoso practice on his “meta-piano” [10]. His idea is to leave the pitch sequence and relative velocity to the sequencer, and to keep one’s fingering focus on articulation, agogic, accents phrasing and nuances[8].

3.2.3 Dynamic models

It is also possible to play pitches by controlling behavioural models [11] that will play the notes following an evolution proper to the model. In that case, a pitch class set can be chosen beforehand, that will be played, mixed, interpolated or triggered according to the model’s behaviour. The authors have presented such algorithms in [12].

3.3 Interfaces for the frequency continuum

Since early XXth century, some electronic instruments allowed to glide from one note to another. The desire to overcome rigid frequency quantification crossed many inventions, and is still subject to new instruments design. Contemporary examples include the Continuum Fingerboard[9], the LinnStrument[10], the Seaboard (Roli)[11] or the Theremini[12] to mention the most known. Each of these instruments tries, in its own way, to bring back together the continuous and the discrete through a more supple change from on to the other.

Though hijacked from its original usage, a commonly used interface as digital instrument is the pen tablet [13]. By offering a highly precise measurement (0.1 mm precision, sampled at 200 Hz), this 2d surface has been used for prototyping many innovative instruments. The pen tablet proved to be a good controller for speech intonation, at least as good as the natural voice during a mimic task experiment [14]. The case of musical sequence imitation is more difficult than simple speaking intonation which does not require as much pitch accuracy as music. A recent experiment from the LIMSI’s lab reported that while some persons manage to sing with their natural voice as accurate as with the tablet, most of the subjets played more accurate with the tablet than with own voice [15].

In LIMSI, we chose a linear mapping of the pitch on the X-axis of the tablet for our Cantor Digitalis instrument. To help the user play in tune, we added a keyboard-based printed layer on the tablet (Figure 2). Its interest resides in the transformation of the traditional discrete and non-linear spaced pitches traditional keyboard into a continuous and linear one, while keeping the keyboard marks for people with a keyboard playing background [16].

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[7] `http://en.wikipedia.org/wiki/Samchillian`

[8] See performance example here: `http://youtu.be/KAtROd5mus8`

[9] `http://www.hakenaudio.com`

[10] `http://www.rogerlinndesign.com`

[11] `https://www.roli.com/seaboard/`

[12] `http://www.moogmusic.com/products/etherwave-theremins/theremini`

4. PLAYING TECHNIQUES

Playing pitches can be envisaged as a ternary process: playing in the frequency continuum by sliding freely on unscaled pitches, playing on the scale with all classical ornaments like trills and such, and modulating inside the scale with vibrato and bends. We tried to organize these parts logically, in order use them in a complementary manner. The Figure 3 illustrates this organisation, which can be found in its Max implementation.

4.1 Pre-scale processing

4.1.1 Continuous surface mapping

In the case of digital instrument, the hardware interface provide sensor values which may not be directly correlated with the axis of intended playing gestures. A first mapping stage will convert the sensors output from the interface to a pitch-wise ergonomic coordinate system.

The Voicer [17] allows to control the pitch along a spiral path on the tablet, one round being associated to an octave (Figure 4). The HandSketch [18] lets the user move the pitch along a curve corresponding to the arm curve around the elbow. A similar idea can be found in experimental acoustic pianos which feature a curved keyboard [19]. The Figure 5 compares these two interfaces.

Other examples of surface mapping are encountered by the authors. They include: chaotic curves to deliberately play chaotic pitch patterns while keeping gestures consistent to the surface dimension; scales with a repeated note to get a kind of drone effect; multiple heterogeneous pitch ranges; and octave interpolations.

4.1.2 Glissando

A glissando is a glide from one pitch to another. It can be achieved continuously on non-fretted string instruments such as cello by moving along the cello board. On a device like a pen tablet or similar continuous surface sensor, the gesture will be similar. Since the sensors sampled values usually operate at a lower rate than audio, data should be smoothly interpolated at audio rate to prevent clicks in the audio signal.

4.2 Octave key, register shift and transposition

Due to the dominating organisation of pitches on octave, the octave key still remains of high interest in DMI, as it makes it possible to reach other registers —lower or higher pitched— while preserving the spatial equivalence of notes on the instrument topology. Furthermore, it allows to extend the potential register of an instrument, while keeping the pitch layout to a small size. We find such a system on numerous synthesizers, often as a double incremental key allowing to rise or descend one octave. Apart from the octave which is a special case, the transposition of the whole pitch layout can help the player adapt to various concert pitches, to perform score written for transposing instruments (e.g. clarinet), or to purposely detune the instrument for stylistic reasons.

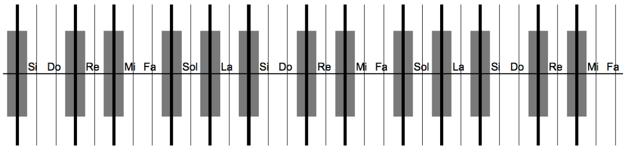
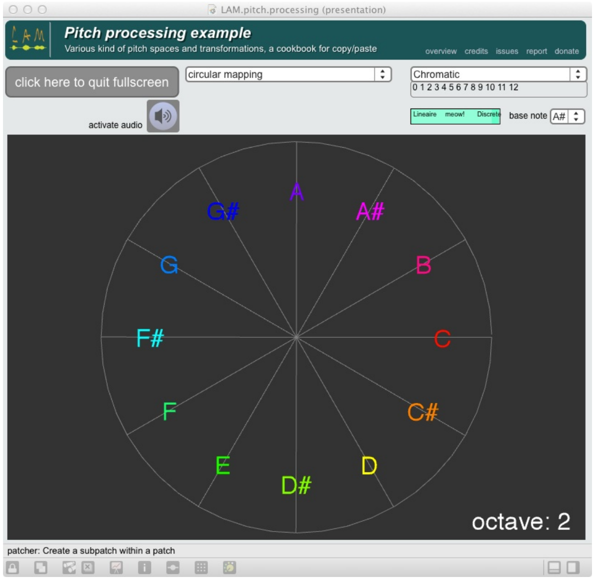


Figure 2: The Cantor Digitalis keyboard from LIMSI. All the vertical lines correspond to the chromatic pitches. The bold lines fit with the traditional keys boundary. Bold lines between Si and Do (B and C) and between Mi and Fa (E and F) are missing to ensure the pitch linearity.



circular mapping

Chromatic

0 1 2 3 4 5 6 7 8 9 10 11 12

base note A#

patcher: Create a subpatch within a patch

Figure 4: The spiral mapping of the pitch illustrated by the LAM-lib, as used in the Voicer. In the LAM-lib, octave is automatically shifted each time the reference note is crossed, to preserve pitch continuum.

4.3 Mapping to scale

4.3.1 Scales bank

An essential organisation of pitch is the scale, which consists in a restricted set of discrete intervals in the frequency continuum. A great number of tonal and microtonal scales have been stored in our Max patcher, in a bank directly accessible as a list. Scales are stored as a list of intervals expressed in floating point semitones, relative to an arbitrary root note set to zero. The last interval in the scale represents the wrapping interval. As an example, for most scales which are based on the octave equivalence, the last interval will be 12. But scales not based on octave like Bohlen-Pierce (wrapping on the tritave), or scales that simply do not wrap at all, are also possible in this system.

4.3.2 Adaptative scales

a) Adaptative stiffness of fretting

As part of the OrJo research project (2009-2012), supported by the *Agence Nationale de la Recherche*, the LAM laboratory developed several algorithms in order to inter-

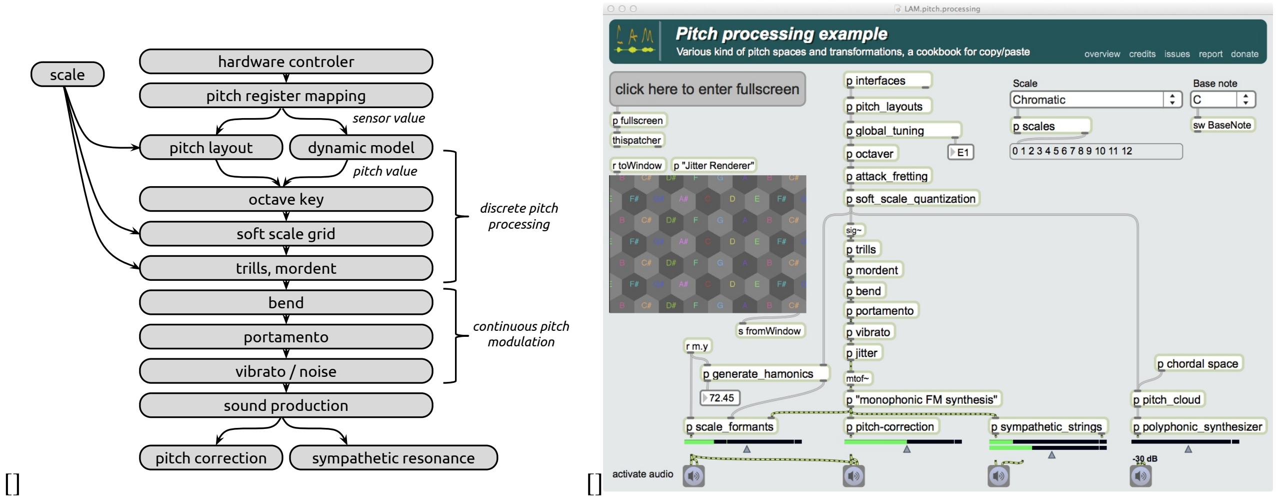


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Figure 3: Schematic overview of (a) the pitch processing modules and (b) the associated Max patcher.

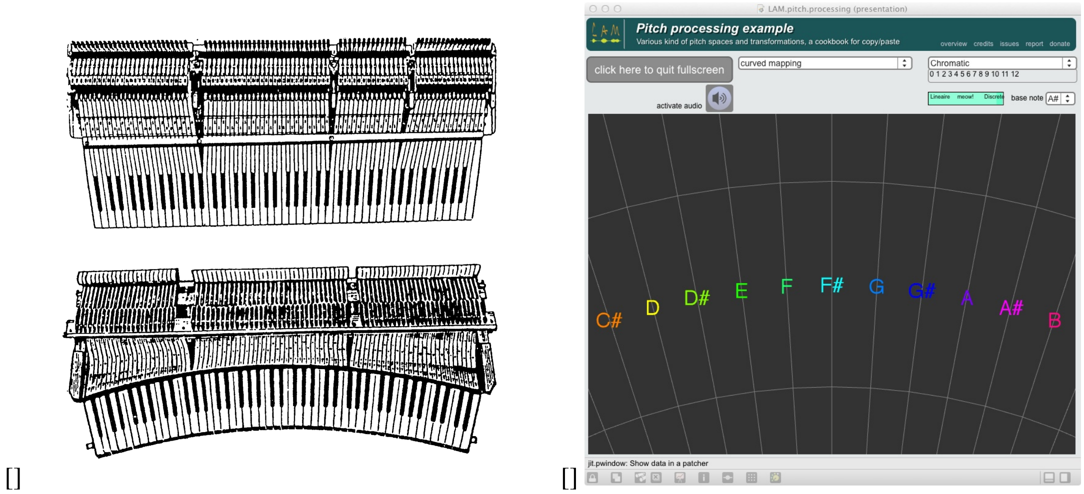

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Figure 5: (a) Two ergonomic keyboards: the upper one features different key orientations while the lower one features a curved keyboard (from Haury [19]). (b) The curved mapping of the pitch implemented in the LAM-lib.

polate smoothly between continuous pitch and quantized-to-scale pitch.

A parameter ranging from 0% (continuous pitch) to 100% (discrete pitch) allows to control the fretting steepness. Three variations of this function exist: *cat*, *dog* and *sigmoid*. The first two owe their name to the smooth ("meow") or steep ("woof") transition between two pitches in the scale. The third is a compromise between *cat* and *dog* versions (Figure 6).

These modules take a pitch value as input, as well as a list of floating point values representing the scale.

The *LAM.quantize.cat* goes as follow:

- Let P_{in} the raw pitch value to be quantized
- Let S the list of pitch values representing the scale
- Let $Z \in [0,1]$ the fretting steepness.
- We search for P_0 and $P_1 \in S$, the closest scale values surrounding P_{in}.
- $I \leftarrow (P_1 - P_0)/2$
- $A \leftarrow P_0 + IZ$
- $B \leftarrow P_1 - IZ$
- IF $P_{in} < A$, $P_{out} \leftarrow P_0$
  ELSE IF $P_{in} > B$, $P_{out} \leftarrow P_1$
  ELSE , $P_{out} \leftarrow P_0 + (P_{in} - P_0)\frac{P_1 - P_0}{B - A}$

b) Attack fretting

Being able to start in tune on a non fretted surface is another challenge. We can easily and quickly catch the right pitch by ear-adjustment, but this is not always a satisfying answer. The LIMSI [20] developed an adaptative system allowing to get a perfectly quantized pitch at attack time by dynamic anamorphosis of the pitch scale (see Figure 7.

The LAM developed a new version of this algorithm to address non-chromatic scales, and stick to the closest degree in a possibly microtonal scale. Considering X_0 the input pitch at contact and P_0, P_a and P_b to be the closest pitch, pitch directly below and directly above in the wanted scale, the gamma coefficient of the curvature is given by the formula:

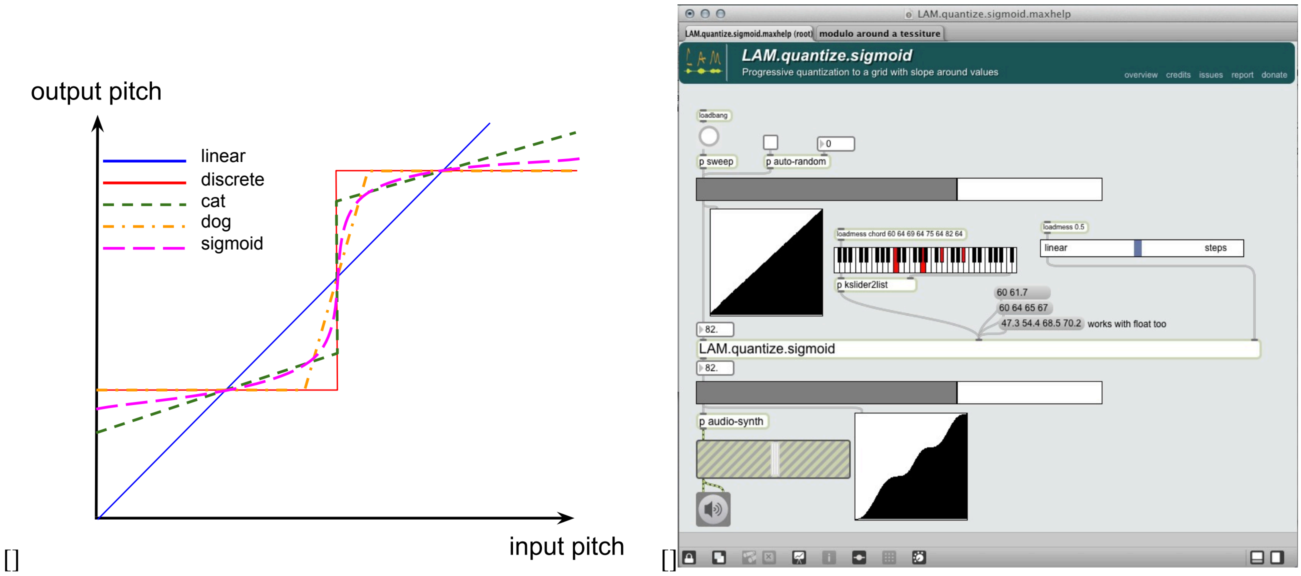

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Figure 6: (a) A schematic view (detail) of a pitch transition between *cat*, *dog* and *sigmoid* algorithm, and (b) the associated Max patcher.

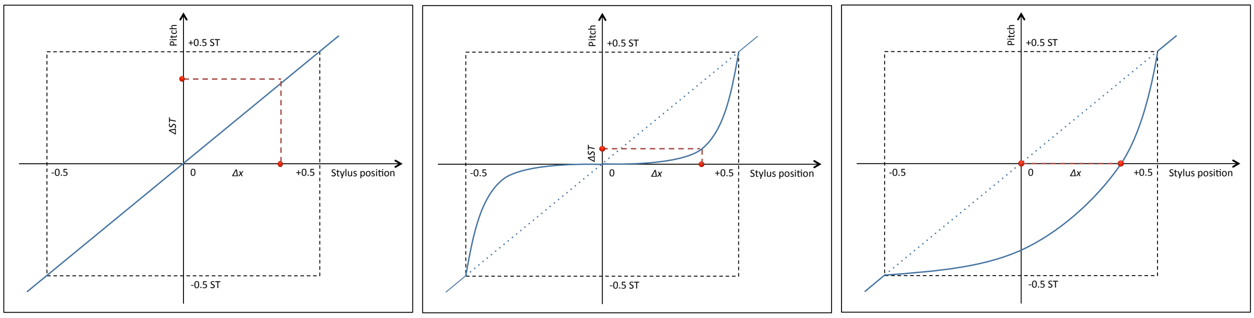

Figure 7: Mapping between pen position and pitch with relative coordinates. Left: linear mapping. Middle: mapping with constraint on pitch position. Right: mapping without constraint on pitch position. From Perrotin & d'Alessandro [20].

$$\gamma = \frac{ln(P_o - P_a) - ln(P_b - P_a)}{ln(X_0 - P_a) - ln(P_b - P_a)} \tag{1}$$

and the output pitch Y can be computed from the input pitch X with the formula:

$$Y = \left(\frac{X - P_a}{P_b - P_a}\right)^{\gamma} \tag{2}$$

4.4 Scale-relative modulation: mordent, trill, gruppetto, turn, arpeggio, fall

All these ornaments are usually played relatively to the current scale, potentially altered. A trill consists of a rapid alternation between two close degrees. A mordent is similar but limited to a single alternation. Also, the alternation rate can depend on the tempo.

It is hardly achieved with some acoustical instruments, like with the natural voice, but possible with their digital analogues. For instance, using DMI to modelize the voice, D'Alessandro & Dutoit [18] combines the continuous control of the graphic tablet to perform portamenti and FSR [13] buttons added on the tablet to perform trills using guitar-like techniques.

The LAM implemented automatic audio rate trill, taking a positive or negative degree, and the current scale, as arguments. The release of the trill is made by setting the degree to zero, and the algorithm will automatically ensure that the trill finished the last note properly.

4.5 Post-scale modulation

4.5.1 Portamento

The portamento is a short slide from one note to another. This technique can be eased by the space-wise interpolation of the adaptative fretting we described earlier in section 4.3.2a) But this smooth transition can also be accomplished with a time-wise interpolation.

A time ramp could produce this effect, but a more interesting and lively way is to lowpass-filter the pitch change. Then we will have 2 parameters to control the effect: the filter frequency F and the resonance Q. However, for a better ergonomy, we can express the resonance in term of half-time release (T), with the formula: $Q = 10^{-1/T}$.

This algorithm provides both smooth transition when set with values such as $F = 2\ Hz$ and $T = 500\ ms$, or vibra-

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[13] force-sensing resistor

Figure 8: A Saraswati veena, with its scalopped fretboard.

Figure 9: A Gibson Les Paul equipped with a Bigsby whammy bar.

tion melting with vibrato with settings such as $F = 7\ Hz$ and $T = 5000\ ms$. With F set to high values, it also produces interesting and brassy transitory attacks.

4.5.2 Bend

The bend is an effect usually made on string instruments like the guitar, achieved by pulling a string to shift temporarily the pitch a few semitone higher, but one can only bend the note to a higher pitch typically a few semitone higher- due to the instrument structure. The only possible way to lower the string's pitch is to "unbend" a pre-bent string [14] .

A fretted guitar fingerboard can be scalloped by scooping out the wood between each of the frets to create a shallow "U" shape. The result is a playing surface wherein the guitarists' fingers come into contact with the strings only, and do not touch the fingerboard. This feature increases the ease and range of string bends by eliminating friction between finger and fretboard. The scalloped fretboard, a feature also present on some Indian instruments such as the veena (Figure 8, facilitates the rapid, microtonal variation that is important in Indian music. Without scallops, the guitarist must play microtones by sliding the string sideways on the fret.

For electric guitars, some mechanical systems, developed since the 1930s, are used to produce pitch variations by changing the tension of all strings simultaneously, typically at the bridge, using a controlling lever (referred to as a whammy bar, vibrato arm/bar, or tremolo arm/bar, see the Figure 9. The lever enables the player to quickly vary the tension and sometimes the length of the strings, changing the pitch to create vibrato, portamento or pitch bend effects. Some of these mechanisms allow downbends as well as upbends.

On the other side, "pitch bend wheels" that have been implemented on synthesizer keyboards can shift the note to much greater extent and in either higher or lower direction. One of the bend feature is that one should provide effort to produce the shift, but little or no effort to release it and get the pitch back to its original value. Our implementation of the bend reflect this particular feature.

4.5.3 Vibrato

The vibrato is a pitch modulation around a central pitch. It can be characterised in terms of two factors: the amount of pitch variation ("extent of vibrato") and its rate. For soprano's singing voice, the rate of the vibrato typically ranges between 4 and 8 Hz and the extent ranges from 20 to 150 cents [21].

A simple automated implementation consists in modulating the pitch value in semitone with an LFO [15] . Given the rate of the vibrato, this modulation should be sample at least at 20 Hz. In Max the message rate is not sufficient for a regular vibrato, so we implemented it at audio rate. Apart from rate and depth, we added a "sharpness" parameter; it is a saturation of the modulating sine wave, which makes the vibrato more steep as the gain increases.

Though studies tend to prove that the perceived pitch is the mean pitch of the frequency modulated sound [22] [23], our implementation proposes a symmetry parameter (ranging -1 to 1) to place the modulation depth below, above or centered on the modulated pitch.

4.6 Side effects of pitch modulation

The liveliness of the sound of acoustic instruments may be partly due to the fact that pitch modulation is not affecting a single feature of sound but several of them. As an example, [24] observed that features like spectral centroid, loudness, or odd/even harmonics balance are also affected by the vibrato gesture.

A consequence in the implementation design of our modular implementation is the output of raw modulating signal. Depending on the chosen sound synthesis algorithm, it is then possible to use these signals to affect timbre and dynamics.

5. PERSPECTIVES

Many musicians want to be able to play in tune when necessary while keeping the freedom to deviate from purely quantized pitch for expressive reasons. Obviously, the research and methods we describe in this paper do not fully cover the topic, and the implementation we propose are over simplified compared to the complexity of instrumental acoustics.

Furthermore, we do not address at all the issue of polyphony control here, which we will like to address in a next step, nor did we raise the internal evolution of pitch in triggered sound event (such as in Road's glisson synthesis [25]). However we hope this will contribute to give an overview of how pitch can be played in a monodic fashion, from instrument making to the practice of the instrument.

Digital instrument making is still a fairly new art, and many new techniques are yet to be discovered. As Max Mathews was stating some 50 years ago: "There are no theoretical limits to the performance of the computer as a

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[14] One could also detune the string with the machine heads, though it may be difficult to be virtuoso with the latter technique.

[15] low-frequency oscillator

source of musical sounds.” One can bet there is no theoretical limit to the number of ways computer sound can be played.

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