Taming and Tickling the Beast - Multi-touch Keyboard as Interface for a Physically Modeled Interconnected Resonating Super-Harp

Palle Dahlstedt
Dept. of Computer Science and Engineering
Chalmers Univ. of Techn. / Univ. of Gothenburg
palle@chalmers.se

ABSTRACT

Libration Perturbed is a performance and an improvisation instrument, originally composed and designed for a multi-speaker dome. The performer controls a bank of 64 virtual inter-connected resonating strings, with individual and direct control of tuning and resonance characteristics through a multitouch-enhanced klavier interface (TouchKeys). It is a hybrid acoustic-electronic instrument, as all string vibrations originate from physical vibrations in the klavier and its casing, captured through contact microphones. In addition, there are gestural strings, called ropes, excited by performed musical gestures. All strings and ropes are connected, and inter-resonate together as a "super-harp", internally and through the performance space. With strong resonance, strings may go into chaotic motion or emergent quasi-periodic patterns, but custom adaptive leveling mechanisms keep loudness under the musician's control at all times. The hybrid digital/acoustic approach and the enhanced keyboard provide for an expressive and very physical interaction, and a strong multi-channel immersive experience. The paper describes the aesthetic choices behind the design of the system, as well as the technical implementation, and – primarily – the interaction design, as it emerges from mapping, sound design, physical modeling and integration of the acoustic, the gestural, and the virtual. The work is evaluated based on the experiences from a series of performances.

Author Keywords

augmented keyboard, physical modeling, feedback

CCS Concepts

•Human-centered computing → Gestural input; •Applied computing → Performing arts; Sound and music computing;

1. INTRODUCTION

In this paper, I present an unusual instrument and a work, called Libration Perturbed. It consists of a large number of virtual interconnected strings, the properties of which are controlled from a multi-touch keyboard interface, McPherson's TouchKeys [8]. All audio signals in the instrument emanate from vibrations in the actual physical keyboard interface, and its wood and steel casing, and the sound generation is completely based on feedback. The particular design of this work, enforced some novel thinking around mapping from an interface to a large number of strings, requiring a very large number of parameters to be controlled in parallel. Also, the feedback nature of the instrument required the development of several mechanisms to work with feedback under controlled circumstances.

What was learned from this process, including the design process of the instrument, the implementation, and emerging playing techniques, is shared in this paper.

Videos of two performances can be found here:
ZKM Cube: https://youtu.be/KxDD_ouvSHM
VirginiaTech Cube: https://youtu.be/GMy7AUvXmo4

2. RELATED WORK

Keyboard instruments have existed for hundreds of years, and they have evolved through different forms over time. There has also been a lot of experimentation with the forms of it, for example microtonal keyboards, quarter tone pianos, etc. In the synthesizer world, people have experimented a lot with what can be done with the normal keyboard, sometimes complemented with extra input such as monophonic or polyphonic pressure. Some have also transcended it into new interfaces, while keeping the linear left-to-right distribution, with examples such as the Haaken Continuum [5], Madrona SoundPlane,[1] the Linnstrument,[2] and many others. There has also been an increasing interest for keyboards with location sensing, such as the McMillen QuNexus[3] and the ROLI Seaboard product series[4]. While good for expressive synth control, none of these two are really designed for musicians with keyboard technique. They offer more degrees of freedom than usual, but default mappings are very conventional, and it is hard to play like a pianist on them, i.e., to play many notes simultaneously and rapidly, with retained control.

With respect to synthesis, I am not aware of anything similar to the Libration project in keyboard form. A somewhat similar approach to ours, about feedback as a constructive sound source can be found in two recent feedback cello projects [4, 11], except with real strings, not virtual.

2.1 Physical modeling

This project relies heavily on the idea of waveguide synthesis [9], where the travel of audio inside of a physical model (e.g., a string or a pipe) is modeled using one or more delay

[1] https://madronalabs.com/soundplane
[2] http://www.rogerlinndesign.com/linnstrument.html
[3] https://www.keithmcmillen.com/products/qunexus/
[4] https://roli.com/

NIME'19, June 3-6, 2019, Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

lines, together with processing of the sound at the crucial points where it bounces off a solid object, such as the bridge of a guitar. Commuted synthesis [10, 6] is the idea that in a waveguide physical model, computation can be saved by preprocessing the excitation pulse instead of using expensive multi-band filtering on the output to emulate the output resonator, such as the body of a guitar or a violin. Mathematically it does not matter in which order you do it, hence the name. Then using acoustic excitation of virtual strings, commuted synthesis is already a part of the concept because the exciting vibrations from the outside bring the timbral profile of the physical object with them into the physical model.

3. CONCEPT

Every project starts with some constraints, given or self-imposed, or simply because of what is available. It depends on what infrastructures and technologies and tools that are available to you, which skills you have, and what are your current foci. In this section I will elaborate on the design process, because only describing the result is principally less interesting. For a forum like NIME, it is equally interesting how we arrive at our designs.

This project started with an opportunity to do a performance in the 46-speaker dome at ZKM, in connection to a keynote. Time was short, but it was an opportunity too good to miss. I decided to create an immersive instrument with spatiality built in, based on the experiences from a previous instrument project using the TouchKeys sensors [8]. These are multitouch sensors applied to the each key of a normal klavier. They do not hinder any of traditional keyboard playing, but allow for tremendous new possibilities [1]. They are designed in an open-ended fashion, without any standard mappings. The raw data provides touch coordinates and contact area of up to three simultaneous fingers per key, which can be used in any possible way.

In previous projects, I had developed a working infrastructure around TouchKeys, and most importantly, developed mappings and playing techniques that really allowed for augmented keyboard playing. In one project, Living Strings [3], I apply a hybrid acoustic-electronic approach to synthesis, using physical models excited with acoustic vibrations. In this instrument, the overall feel is to interact with a physical, acoustic object.

Keeping that hybrid approach, a completely new virtual sounding structure was created, or rather a huge acoustic virtual harp sculpture with which I can interact during a performance, and hence shape the music both directly as a gesture-based musician-performer, but also by controlling higher-level parameters of the audio beast, hence being able to alter between gesture-based musicianship and sculpting the sound of a large resonating system.

3.1 Design decisions for the sound engine

Before I started, a number of decisions, aesthetic and technical, were taken. The instrument should be a huge resonating harp, with a large number of interconnected strings, based on the idea of resonance. Resonance and feedback have been core concepts in my musicianship for a number of years, because of the complexity it gives rise to, the organic sounding results, because I have developed a number of techniques, strategies to tame it.

All strings should be on, all of the time. As composers, we often think in terms of events. As a synthesist, I prefer to interact with continuous systems, and modulate its parameters. Gestural input is continuous, as is motion and movement. Acoustic instruments are also not really based on events. In a piano the strings are always doing their thing, but you modulate them with dampers, and you inject bursts of energy through the hammers. But the energy is injected into a string that may be already vibrating. It is the same with a drum. You inject energy into an already vibrating membrane. Each injection is different.

With all strings active all of the time, you can still have a lot of control by regulating parameters such as: pitch, injection of vibrations into the string, amount of injection from neighbor strings, target amplitude level, and the bridge filter, which controls the frequency-dependent energy loss when the sound wave in the string bounces on the bridge and goes back into the string again. With the filter high, the string rings brightly for a long time. With the filter is low, it sounds muted (and the pitch goes down). The filter acts as a damper. Usually, more energy is lost in the higher register, so even a simple low-pass filter in a delay feedback loop creates a believable string model (the famous Karplus Strong model [7]). The filter level is also a key component of taming runaway resonances.

3.2 Structure

The structure of the harp is partly determined by the given hardware constraints (in relation to the aesthetic idea). Sometimes this is a good thing, because it speeds up the decision process, and induces a logic to the work.

The decision to use the Nord Modular G2 DSP platform for the implementation of the work comes with quite a few constraints regarding computational load (like every computer), signal flow (because of the limited number of buses between processors and limited number of inputs and outputs), and voice structure. It was decided early on that I would need 4 Nord G2s to be able to produce 16 discrete output channels, as each machine has 4 outputs. Each (expanded) machine has 8 processors, which are dynamically distributed depending on computational load, but are most effectively used in pairs. There is a mechanism for polyphonic patching, meaning the creation of many instances of the same patch, but it is only useful for a system with dynamic voice allocation, and this harp needs all strings to be on all of the time. So a fixed DSP structure was more feasible.

With a decent complexity of each string, one processor can do four strings, with the second processor doing post-processing, panning and other duties. That leaves us with 4 strings x 4 processor pairs x 4 machines = 64 strings, which is a good number, because it is cognitively manageable, is of the same order of magnitude as the numbers of keys on a keyboard, and it can (and has to) be divided into subgroups of 4 per processor pair, and 16 per machine.

For the Living Strings project, I developed a quite realistic waveguide string model that could also emulate prepared strings, i.e., strings stopped with objects of varying hardness. There the focus was on very expressive interaction with a smaller number of strings. In the current project, the focus is on the immersive mass effect of being surrounded by a large number of sounding strings, so each string model does not need to be as advanced.

The simplest physical model string model is the Karplus-Strong, a delay line with a low-pass filter emulating the energy loss when the audio wave traveling along the string bounces on the bridge. With gestural control over the core parameters, such as frequency, damping, low-pass filter, and some added non-linearity (i.e. an adjustable wave folder inserted into the feedback loop), it can produce quite complex behavior.

A standard Karplus-Strong string is started with the buffer filled with noise, and by varying the noise timbral character, different timbres can be achieved (cf. commutable synthesis, mentioned previously). Still, such string models are isolated from the environment, and are perceived as quite "clinical", or dead. If the excitation instead is done by acoustic vibrations in the klavier interface, which by necessity are different each time, the string comes alive in a completely different way. In addition to this, since the fundamental concept is resonance, I want the strings to be excited by their neighbor strings, and from the total sound of the harp.

The number of strings (64) fits within the number of keys on one of my TouchKeys keyboards (73), so one key per string is a reasonable interaction paradigm. In addition to string pitch, control of its dynamics will be of utmost importance, because there will potentially be a lot of energy floating into the string from acoustic vibrations and neighbor strings.

The two opposing forces are the incoming sounds from a variety of sources – which of course is needed for any resonance to happen, and the the damping of the bridge low-pass filter. If the filter is too low, there will be decay, and if the filter is too high, the level will explode. It is technically impossible to keep the string's energy on a constant level without adaptive solutions, similar to how a regular compressor works – dampen the string only if it is too loud. A level mechanism of some kind is needed to tame the beast.

The strings should be connected in a long chain, or circle, so that vibrations to one string will resonate for quite a while, depending on current settings. This resonance will also spread spatially around the room, thanks to the spatial distribution of the speakers.

Finally, there needs to be a mechanism for inducing higher frequency content into the string while it is ringing. In an electronic feedback loop, any non-linearity (such as distortion) will introduce higher frequency content of some kind. I have previously experimented with different kinds of waveshapers in feedback circuits, and a similar mechanism can be used in this instrument.

Strings can be of any size, and so can physical models of them. I wanted some kind of pulsating movement in the harp, and for conceptual consistency, they can be implemented as strings that operate on a gestural timescale of 1Hz or lower. I call them *ropes*. If ropes are excited by what is played (on the regular strings), and can in turn be played by managing their resonance in relation to their neighbor ropes, and feedback just like the audible strings, they can provide an interesting source of both texture and gesture.

The ropes need to modulate something to be heard, since they operate in the sub-audio range. There are several alternatives. They can modulate the damping filter, but that would have a somewhat delayed effect. More effective would be to modulate either the level of nonlinearity (because it quickly induces audible high-frequency content into the string, like when you hold your nail against a guitar string), or the amount of injection from a continuous source, because then it would appear really like a resonance of something.

4. IMPLEMENTATION

Based on the concept design from the previous section, I proceeded to prototype and test a number of potential solutions for each needed building block: simple string models, more complex string models, leveling mechanism, different damping filters, nonlinear waveshaping, a rope model and various mechanisms for rope-string interaction. It turned out that most of the drafted concept worked, but a large number of specifics had to figured out by an iterated design process.

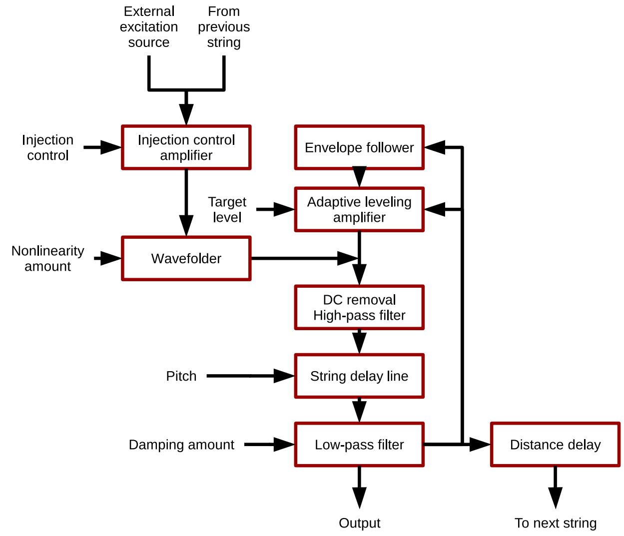

Figure 1: A simplified signal flow diagram of the string model, showing a single string out of the 64. The ropes have a very similar structure, but operates at a gestural time scale.

After trying out several more complex string models, the basic Karplus-Strong ended up the most practical and usable choice, with a simple, adjustable low-pass filter on the bridge. With the extensions of external excitation and the potential of nonlinear waveshaping in the loop, this simple model becomes very powerful. Some of the other tested string models included twin strings slightly detuned, or tuned in integer ratios, etc., and while some sounded quite interesting, they were computationally too expensive.

The most challenging part was to design a robust adaptive leveler, that was fast without overreacting, and which did not consume much computation power. After trying many different candidate solutions, I arrived at a very simple solution:

$$A_t = 1 - k(P_{target} - P_t)$$

$$P_t = \alpha s_t^2 + (1 - \alpha)P_{t-1}$$

where A_t is the gain amplification factor within the string feedback loop, $P_{target}$is the target sound power, and k is the adaptive strength coefficient. Current sound power P_t is calculated as an exponentially smoothed square of the audio sample stream. It is a bidirectional leveler, allowing for absolute level control and infinite sustain (which of course is impossible with real strings). If disabled when $P_t < P_{target}$,it becomes a one-directional leveler, i.e., upwards limiting, but allowing for decay.

Once the leveler was in place, different resonance mechanisms were tested. Basically, a suitable topology for string resonance coupling was needed. Different topologies gave very different results. The simplest solution turned out to be both interesting and controllable: a chain of strings, each injecting into the next, with the option to close the chain into a circle. With adjustable injection strength from the neighbor string, the behavior of a group of strings can range from shimmering resonances over locking in a quasi-periodic coupled patterns to downright deterministic chaos.

The chosen and now implemented string model is, thanks to the adaptive leveler, able to balance between a number of simultaneous opposing forces (see Fig. 1):

- energy injection from nearby strings,

- energy injection from the outside,
- high frequency content generation from the non-linear folding ("nail buzz"), and
- damping/removing of energy with the bridge filter.

4.1 Ropes

The gestural strings, the ropes, were implemented as slowly clocked delay lines, with a filter in the feedback loop, which is basically identical to the audio strings, just with lower frequency and resolution. There is one rope per string group, consisting of four strings.

The mechanism for macro-resonance was designed and implemented as follows:

We know how to create continuous resonances between strings, thanks to the leveler which keeps the sound energy from exploding. But how can one create a resonant texture on a macro time-scale, that contains a granularity and inner detail? This is much harder than a resonant string, maybe simply because a texture contains so much more information. I have previously made experiments with banks of resonators at non-rational frequency ratios to capture resonances at all frequencies – but it was not possible to make them broad enough, spectrum-wise, and they were computationally expensive.

A pragmatic solution was to separate long-term (ca 1 second) audio content and gestural content. Audio is gathered continuously by an adaptive auto-looper, with a looping time of maximum one second. It collects the sound from its string group, automatically adjusting the mix between previous material and incoming material so that is always contains a evenly layered mix of recent activity.

Gestural content is gathered in the actual rope model, which has the volume contour of incoming sound (external and from its own group) as input, and works just like the strings, with adjustable damping.

When modulating the output volume of the adaptive looper with the output of the rope, we get a result which can be described as a kind of textural resonance. This sound is injected into the next string group. The looper usually contains harmonically rich material from the current string group. When this is transformed into a gesture by rope modulation and sent to the next string group, the effect is as if these strings were played again and resonated in the next group of strings, resulting in a ghostly effect of somebody playing inside the instrument, potentially propagating through the string groups, and causing resonance in the next rope.

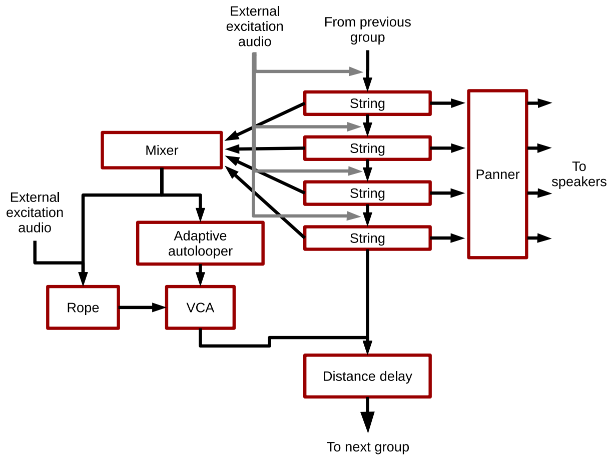

Figure 2: A simplified signal flow diagram of a string group of four strings and one rope, showing a single group out of a total of 16. Each box labeled String contains all of Fig.1.

4.2 Interaction design and mapping

Here I will go through the interactions that are possible with the Libration instrument, through its interface consisting of a TouchKeys-equipped Nord Stage 2EX Compact keyboard, two piezo contact microphones attached to the top and bottom steel surfaces or the keyboard casing, and a number of knobs assigned to MIDI controllers.

4.2.1 *The main interaction model*

Each key surface represents one string, with 64 out of 73 keys used. Through pressing a key and/or touching its surface in various ways and in different positions, the parameters of that specific string can be controlled, such as pitch and damping. External audio is injected into a string when its key is pressed. The constant amount of sound injected from the neighbor string is controlled with a global knob.

All strings are active at all times. A string may still be quiet if its damper filter is set low, or if it has not yet received any excitation.

A key-down gate signal opens the injection to the corresponding string, and keeps it open as long as the key is held. This lets the sound from the piezos into the string, and makes it vibrate. The very "thunk" vibration from the pressing of the key can be enough to excite the string. Or the key can be held while you scratch the metal with your nail, or scream into the sheet metal casing. When the key is released, the string continues to resonate, and may decay or sustain depending on the current damping for that string and the global leveling settings and target level.

A sustain pedal opens all strings to external input at once. This is a quite strong effect, because the whole room starts to resonate, and there is potential for room feedback.

4.2.2 *Control of each string*

String pitch is decided by depth-wise finger touch position. The further in on the string you touch, the higher the pitch. This can be controlled while playing, with high precision, and allows for complex pitch gestures. When the finger is lifted, the pitch stays at its last value. Touching a key without pressing it has no effect – it is very difficult not to touch a large number of keys when playing with normal piano technique, as keyboardists (to a varying degree) use the sense of touch to navigate the keyboard.

String damping is modulated by touch area (large area lowers the filter), global modulation wheel, and aftertouch pressure (more pressure lowers the filter). The metaphor here is that pressing on a string or placing the cushion of your finger on it will dampen it.

Two fingers at the same key raises the amount of wavefolding, drastically increasing the harshness of resonances.

A control pedal sets global target amplitude level for all strings. The leveling mode (bi-directional or upwards only) is selected with a knob.

4.2.3 *Global parameters*

Some global parameters do not need gestural control, and are assigned to regular knobs. The following global parameters are available:

Leveler target mode: decay or steady level.

Panning rotation speed

Feedback amount, how much to inject from neighbor string.

Inter string distance delay time, up to 500ms.

Rope modulation level

Global rope length control, the speed and maximum gesture time of the rope.

Rope damping, how fast the rope gestures decay (or build up).

4.3 Taming the beast

During a number of recent project, a number of techniques and strategies for controlling feedback have been developed. Thanks to these, the organic qualities of feedback systems (which approach those of physical models, because the two classes of systems overlap) can be kept, without ending up with howling sounds nor broken eardrums. Here is a list of these strategies:

Make sure that no node in the feedback system sends audio to itself. Always have something in between, preferably something that induce a delay to the signal.

Take control over the resonances (their quality, through filters etc.) and when they are allowed to pass. Never just let them sound all the time - always have access to a mechanism to break or modulate the feedback chain. Direct playing on feedback connection strengths with some interface is a surprisingly expressive interaction model.

Take control over the feedback path, and use long loops. Longer delays increases build-up time.

Avoid total connectivity.

Avoid reinforcement, i.e., positive feedback. Find ways to modulate so that high levels/durations will lower the levels/durations. Then you can achieve a stable system.

Use selective level- and duration-controlled feedback. For example, reasonably soft levels can increase resonances (feedback), while loud levels do not. Reasonably sparse signals may trigger resonances (feedback) while continuous signals do not. This can be implemented as an A-shaped feedback response curve – only middle levels result in feedback.

Play the feedback system: Take gestural control of resonance and feedback features, of injection of gestural material, and of specific parameters (string length, feedback level, etc.).

For an unstable feedback system where essential parameters are under gestural control, you can apply navigational strategies such as: probe and react, find and rest, explore and contemplate (what you have before you lose it). Or ponder and vary, discover and exploit, or possibly even: go to the limit and jump ship (these ideas are further developed in [2]).

All you need is careful listening, mechanisms for reverse movement and direction change in parameter space. With this approach, you can even perform on the levels of a fully connected feedback matrix.

In the Libration instrument, a number of these mechanisms are applied. For example, the direct string feedback passes through 64 strings before it gets back to where it started. Between all those strings there are delays, so the time for build-up can be controlled. There is adaptive control of string volume, and global controls for lowering damping filters and global target levels at any moment. Even if the whole room starts to resonate through the pick-ups into the strings and out to the speakers again, with the pedal down, it doesn't explode.

4.4 Spatialization

This piece was composed for the ZKM surround sound dome in Karlsruhe, Germany, with 46 speakers. Because of the hardware constraints, I provided 16 channels, which were distributed around the dome in an upwards spiraling pattern, with 8 channels in the lower ring, 4 in the middle, 3 in the top ring, and 1 channel in zenith. However, individual strings are panned in between output channels, so that a higher spatial resolution is achieved. There are 16 strings per four 4 channels, distributed evenly, and there is a possibility of automated rotational panning, with control over direction and movement.

The piece has also been performed in the multi-speaker cube of Virginia Tech (at NIME18), with a similar spatial distribution of the audio channels.

The spiraling distribution of channels was chosen for several reasons. The set of 64 strings are connected in a long chain. This means that if a loud sound is injected in one string, one can hear it propagate to other strings, which now becomes a movement, not a series of jumps. I wanted to preserve the basic structure of a long chain, and chose to represent it as a spiral. Also, keeping it as a linear structure makes it easier to mentally map the keyboard to the spatial distribution, as the strings are distributed along the keyboard. The upper part of the keyboard corresponds to speakers high up in the ceiling. In addition, it is easy to produce a sparse spatial distribution by playing on strings far apart on the keyboard.

To provide for further spatial animation, I implemented a rotational panning algorithm, with control over direction and speed. It rotates the 16 strings of each machine linearly along the four output of the same machine. There is no way to do a proper linear motion across all 16 channels due to the distributed hardware, but the effect is nearly indistinguishable from a complete rotation; a kind of barber-pole movement.

4.5 Infrastructure

Due to the extent and multiplicity of the synthesis model, and the distributed hardware, the infrastructure of the work is rather complex.

First, the interface setup: The TouchKeys sensors are connected to the computer through USB, and its accompanying (open sourced) software generate messages using the OSC protocol. I use the raw data OSC frames, as the built-in mapping options are not sufficient for what was needed. The OSC data, together with the MIDI data from the keyboard and knobs, are sent to a custom mapping program implemented in OSCII-bot,[5] a free programming language for OSC and MIDI management. The mapping code keeps track of which key is down, pairs OSC data about keyboard touch with the right MIDI data, stores latched values for key surface coordinates, routes messages to the right part of the distributed synthesis engine, and a lot more. The output is a steady stream of MIDI messages, which is sent onto the four Nord G2 through a 4-port MIDI interface, on four channels each, one for each string group.

The four Nord G2 have four audio inputs each, and four outputs. All G2 receive input in one channel as a mixed and preprocessed signal from the two piezo microphones attached to the steel casing of the performance keyboard.

Each G2 send out the output of its 16 strings, panned linearly over the four output channels. Output no.4 of each Nord G2 is split and sent onto the next machine, to keep the chain of string connections unbroken. The last one is (optionally) connected back into the first. If it is, then the 64 strings form a circular configuration. If not, they are a long chain with a beginning and an end. The behavior is quite different between the two configurations.

Before a performance, I do a feedback test in the room to find the strongest room resonances, which are then reduced using a parametric equalizer to avoid strong feedback peaks. The instrument can handle the levels, but it is not nice

[5] `https://cockos.com/oscii-bot/`

when a few frequencies stand out all the time. Also, some undesirable resonances happen in the steel casing of the performance keyboard, and are similarly reduced.

5. PLAYING TECHNIQUES

With any new instrument, during testing, rehearsals and performances, recurring playing techniques emerge. By looking at these, one can draw some conclusions about how the instrument works, and especially about what are the important aspects of the current specific implementation of the more general idea. This is part of my method, and sometimes the results are quite unexpected. Minute implementation details may end up being treated as core features in concerts, and vice versa. Also, a list of common playing techniques and "devices" is very useful when developing the next instrument, or the next generation of the current instrument.

5.1 Observed playing techniques in Libration

Below I will list a few playing techniques that I have observed during my playing, and give some explanation when needed:

Hold key and inject sounds - this is the basic technique, as the system was designed. Holding a key means it is open for injection of excitation sounds, so any noise into the piezos will make the string sing.

Hold chord and inject sounds - when holding several keys, you have to remember that this is no ordinary keyboard. Pitch simply is not mapped to key, but instead mapped to the keyboard depth-wise position. The effect is similar as the previous technique, except that you simultaneously inject the same noises into all held strings.

Press down the sustain pedal and hit the whole machine on the end-cheeks, or stomp on the floor. This is a very powerful technique, because it opens up the whole harp for acoustic input, which then becomes quite reinforced because of the multiplicity of the signal. Also, any remaining room resonances can cause specific strings to scream. But as soon as you lift the pedal, the mayhem stops. Or, depending on the damping settings, etc., the only thing that happens may be that there suddenly is a strange sonic atmosphere around the room.

Hold a few string in high register and play very clear resonant soft treble sounds

Hold a few keys and make pregnant rhythm. This triggers the rope gestures, and with the right settings (low rope damping, high rope modulation out), these rhythms may keep playing on for quite a while.

With long or medium-long inter-string delay, play short sounds. These then propagate through resonances in successive strings, which are distributed around the room.

Raise the global feedback level. In the middle the strong drone, use pressure and key touch area to modulate down the damping filter (mute the drone), and suddenly play a single sound or a few keys - then the drone comes back when I release

Tapping with low string damping filter. With the damping set very low, tapping strings (or rather, tapping the metal casing when holding a key) has a very acoustic sound, like rubber bands.

Ritardando of gesture tempo. Record gestures and enable the ropes. Once they are all playing, slowly lower the rope speed. The gestures keep playing.

Hold a number of strings and scratch the heating vents no the back of my Nord Stage keyboard - was it maybe secretly intended as a *guiro*?

In the middle of a drone, raise the damping filter of one string at a time, then remove again. These strings will be clear as glowing points in a gray mass.

In the middle of a drone, gradually change the pitch of all strings, a few at a time, from high to low or opposite.

5.2 Performance

Libration Perturbed is an instrument/work designed for improvisation, and the performances have been quite different. Because of the high degree of nonlinearity, it is hard to predict what will happen. On the other hand, there are tools for dealing with whatever will happen, through the detailed mapping. One will not be stuck.

Generally, I start by feeling in the room, and exposing the sound sources in the dome by playing rather pointillistically. Gradually I explore the stronger feedback settings, getting to stronger self-oscillating drones, and alternating between them and precise gestures on one or a few strings. I usually save the ropes for the second half, where they work like a kind of accompaniment, which I have to "refill" once in a while. Also, the rotational panning is saved for the very end.

6. CONCLUSION

I have presented a beast of a feedback instrument, played by being tickled by acoustic sounds and tamed through a well-working mapping and internal adaptive leveling mechanisms. I dare tickle it, and it can be tamed.

7. REFERENCES

[1] Dahlstedt. Expert commentary: Turning the piano keyboard inside out. In *A.R. Jensenius, M.J. Lyons (Eds.): A NIME Reader: Fifteen Years of New Interfaces for Musical Expression*, pages 430–432. Springer, 2017.

[2] P. Dahlstedt. Circle squared and circle keys - performing on and with an unstable live algorithm for the disklavier. In *NIME14*, pages 114–117, London, United Kingdom, 2014.

[3] P. Dahlstedt. Physical interactions with digital strings-a hybrid approach to a digital keyboard instrument. In *NIME17*, pages 115–120, 2017.

[4] A. Eldridge and C. Kiefer. Self-resonating feedback cello: Interfacing gestural and generative processes in improvised performance. In *NIME17*, pages 25–29, Copenhagen, Denmark, 2017. Aalborg University Copenhagen.

[5] L. Haken, E. Tellman, and P. Wolfe. An indiscrete music keyboard. *Computer Music Journal*, 22:1:31–48, 1998.

[6] M. Karjalainen, V. Välimäki, and Z. Jánosy. Towards high-quality sound synthesis of the guitar and string instruments. In *ICMulfarC93*, pages 56–56, 1993.

[7] K. Karplus and A. Strong. Digital synthesis of plucked-string and drum timbres. *Computer Music Journal*, 7(2):43–55, 1983.

[8] A. McPherson. Touchkeys: Capacitive multi-touch sensing on a physical keyboard. In *NIME12*, Ann Arbor, MI, USA, 2012.

[9] J. O. Smith. Physical modeling using digital waveguides. *Computer music journal*, 16(4):74–91, 1992.

[10] J. O. Smith. Efficient synthesis of stringed musical instruments. In *ICMC*. ICMA, 1993.

[11] H. Úlfarsson. The halldorophone: The ongoing innovation of a cello-like drone instrument. In *NIME18*, pages 269–274, 2018.