Physical Interactions with Digital Strings - A hybrid approach to a digital keyboard instrument

Palle Dahlstedt

University of Gothenburg
Dept. of Computer Sc. & Engineering
Division of Interaction Design
SE-4126 Gothenburg, Sweden
palle.dahlstedt@gu.se

Aalborg University
Dept. of Communication & Psychology
Rendsburggade 14
DK-9000 Aalborg
dahlstedt@hum.aau.dk

ABSTRACT

A new hybrid approach to digital keyboard playing is presented, where the actual acoustic sounds from a digital keyboard are captured with contact microphones and applied as excitation signals to a digital model of a prepared piano, i.e., an extended wave-guide model of strings with the possibility of stopping and muting the strings at arbitrary positions. The parameters of the string model are controlled through TouchKeys multitouch sensors on each key, combined with MIDI data and acoustic signals from the digital keyboard frame, using a novel mapping. The instrument is evaluated from a performing musician's perspective, and emerging playing techniques are discussed. Since the instrument is a hybrid acoustic-digital system with several feedback paths between the domains, it provides for expressive and dynamic playing, with qualities approaching that of an acoustic instrument, yet with new kinds of control. The contributions are two-fold. First, the use of acoustic sounds from a physical keyboard for excitations and resonances results in a novel hybrid keyboard instrument in itself. Second, the digital model of "inside piano" playing, using multitouch keyboard data, allows for performance techniques going far beyond conventional keyboard playing.

Author Keywords

Augmented keyboard, Musical keyboard, Multi-touch, Mapping, Gestural interfaces, Physical modelling

ACM Classification

H.5.5 [Information Interfaces and Presentation] Sound and Music Computing H.5.2 [Information Interfaces and Presentation] User Interfaces — Auditory (non-speech) feedback

1 INTRODUCTION

Keyboard instruments provide an interface optimized for a large number of notes, but little control of each note. New sensing technologies could, in theory, change that. This paper presents a novel keyboard instrument, which combines features from acoustic instruments with digital sensing and control. The instrument, for now called *Living Strings*, is meant to be an answer to two questions, one related to technical curiosity, the other to a long-term artistic search:

1. When multitouch sensors for normal keyboard interfaces are available, how can these be used to allow for extended control of electronic instruments?
2. How can we design electronic instruments that allow for the kind of musicianship denoted by the German and Scandinavian word "*musikant*" – a musician embodying the music and the joy of physical playing, and is a hybrid instrument, integrating digital and acoustic techniques an answer to this question?

NIME'17, May 15-19, 2017, Aalborg University Copenhagen, Denmark.

The instrument is developed by and for a keyboard performer (myself), and the main focus is not on correct physical models, but on finding an effective interaction model that allows for expressive, dynamic and varied playing, with intimate control over pitch, dynamics and timbre, while taking advantage of the motor skills acquired from years of musical practice.

The reasons for this focus is simply that this instrument is developed to be used, in a wide variety of improvisational contexts, solo, with other musicians, and together with other kinds of stage performers (e.g., dancers). In such contexts, you either repeatedly develop something adequate for the temporary context, or try to design an instrument diverse and expressive enough to be applied in all these contexts.

The instrument has specific qualities from the merging of acoustic excitation with a virtual string model, and controlling this from a rather new multidimensional digital keyboard interface. It is evaluated based on the aesthetic results and playing techniques that have emerged during the prototyping phase, the hybrid electronic/acoustic qualities of the instrument, and from how it bridges the physical/virtual divide.

This instrument is part of a series of artistic research projects developing for new electronic instruments and technologies for improvising musicians.

2 BACKGROUND

2.1 Pre-history

Living Strings stems from a previous hybrid electric-acoustic keyboard instrument, augmenting an acoustic piano with virtual strings [1]. When this project was implemented with digital keyboards, a contact microphone was sometimes added to the instrument panel to allow for the same kinds of physical interactions as could be applied on an augmented acoustic piano, such as knocking or scratching. At some point, this feature was tested on its own, and a digital keyboard instrument based on acoustic excitation was born. This was merged with the newly presented TouchKeys sensors [2], and with an expanded string model, it is now a mature instrument.

2.2 Previous art

There are a number of existing instruments and products based on touch and physical interactions with object, combined with digital or analog processing, such as Enrique Tomas' *Tangible Scores* [3], and the Mogees add-on for iOS devices based on a contact microphone and software.[1]

Physical models of strings have developed far from the early Karplus-Strong algorithm [4], into complex waveguide synthesis [5, 6, 7], and even specific models for prepared piano strings [8]. An overview of virtual acoustic instruments can be found in [9].

Physical models have inspired physical interfaces, for example in the merging of multitouch surface meshes with physical mesh models of vibrating membranes [10]. One particular point of inspiration has been Carla Scaletti's work Slipstick[2], where physical

[1] http://www.mogees.co.uk/

[2] https://youtu.be/eAVLrtOrcyc

models of friction and vibration forms the basis both for performance method and sound synthesis.

One important point of departure for Living Strings has been the idea of commuted synthesis [11,12], which originally was a way to simplify physical models using the insight that the complex filtering done by the final resonating body of an instrument could be pre-applied to the excitation impulse, since an ideal string model is a linear system, and those characteristics are retained. However, in Living Strings, this becomes a core feature. The excitation impulse comes from vibrations in the actual keyboard, and thus embodies its acoustic imprint, and brings that into the virtual string model.

2.3 Method

This project is an example of practice-based artistic research, combined with research-based practice, according to Smith's and Dean's model [13]. Based on a clearly stated problem and the given premises, a number of iterated prototypes are developed, trying to solve the problem. Each iteration is evaluated qualitatively, through extensive practice and playing, possibly tested in preliminary performances. When a sufficiently plausible result is achieved, the design is frozen, and used in a large number of performances and recordings, often over several years. This is part of the long-term evaluation. Then, the instrument is evaluated again, with a focus on the playing techniques that have emerged over this time. With these as a departure point, we are able to see the relationship between design choices and implementation details on one hand, and the aesthetic results on the other.

The Living Strings project is currently in the early part of the long term evaluation phase. Early prototypes have been used on stage, and based on experiences gained from that, a sufficiently good design has been developed, frozen, and used in a series of concerts.

3 IMPLEMENTATION

3.1 Hardware and software platforms

The Nord Stage series of keyboards are well-known digital pianos, which have been on the market since 2006. They are crafted in heavy steel with wooden birch sides. These robust materials make the panels eminently playable. Furthermore, the Nord series of keyboards feature a pitch stick instead of the more common pitch wheel. This stick is a piece of wood mounted on a piece of spring steel with a bend sensor. Thanks to this construction, it can be used as an interesting excitation source. Finally, these keyboards have a large number of buttons emitting a bright spectrum when clicked.

For signal processing, the Nord Modular G2 platform has been used. It is robust, has high internal precision (96kHz/24bit resolution) and is very quick to program. There are some limitations. E.g., it is MIDI only, which is a limiting factor due to the high bandwidth of sensor data required for this kind of instrument. Emulating 8 strings, it is currently at the limit of its capacity, and future version will most likely be implemented in Kyma[3], which has native OSC support.

3.2 Sensors

There are now a number of continuous keyboard and surface controllers available, which could in principle be used for this project. Some of them, like the Madrona Labs SoundPlane[4], can be used as a 2-dimensional keyboard, but lack distinct keys. The Roli Seaboard[5] is a foam-covered surface of keyboard-like geometry, with multitouch and pressure sensitivity, but its wedge-shaped key design prevents any advanced keyboard technique to be used, and seems to be mainly aimed towards non-keyboard players. As a trained keyboard player (piano, harpsichord and clavichord), I want to take advantage of the motor skills I have developed over years of practice. The TouchKeys sensors are currently the only available sensors which are applied on a normal keyboard action.

TouchKeys is a set of capacitive sensor plates, installed permanently on top of the keys on an existing keyboard or piano, with supporting electronics on PCBs mounted inside the keyboard. It is connected to a computer via USB, and its custom software provides an interface for configuring customized mappings, communicated further through the OSC and/or MIDI protocols. There is also a possibility to receive all sensor data in raw form through OSC, for other kinds of mapping, which is used here.

A disadvantage compared to some other keyboard sensor interfaces is that the TouchKeys do not provide pressure. The TouchKeys output is made to be combined with other keyboard data from the keyboard controller it is mounted on. It could in principle be mounted on a keyboard with polyphonic aftertouch, but those are hard to find, especially if piano-like action is preferred. So, this was not possible for this project. However, with contact area data provided for each finger, together with channel aftertouch information, TouchKeys provides a rich set of performance data.

The musical potential of TouchKeys has previously been discussed [14], concluding that, without being an obstacle to trained keyboard skills, it adds the ability to go deeper into each single note, and alter between these two different states. What comes out of this of course depends on the chosen mapping and sound engine.

3.3 The String Model

The physical string model is based on wave-guide synthesis [5, 6, 7]. Departing from a well-known waveguide model of a perfect string, which divides the string into four segments, two in each travel direction, representing the stretch of the string on each side of the "pick" position where the excitation impulse is injected (see Fig. 1).

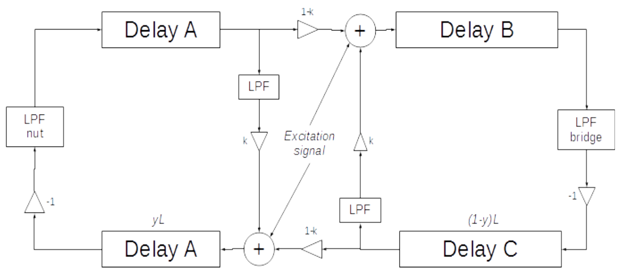

Fig. 1: A simplified schematic of the plucked string model used, where L is the total string length, y is depth position on the key, k is the amount of stopping.

In each end, the bridge and nut are represented by low-pass filters and a 180 degree phase shift. To this basic model, I have added a simple representation of what happens when the string is "stopped", i.e., when an object (finger, fret, etc.) is pressed against the string.

This is implemented as a crossfade between just passing the wave through the injection point (while adding the external injected feed), and bouncing it back. On a real string, a soft object on the string, such as a finger held with a light touch, would let some sound pass through, and bounce some. A rigid object pressed hard against the string would instead reflect everything, just like a new bridge, inserted at the injection point. In effect, it turns the string into two sub-strings, with a moveable midpoint (see Fig. 2 for the actual implementation).

Normally, when a wave is reflected by a rigid object such as a bridge, it is inverted, which in effect doubles the periodicity of the wave. In this implementation, inversion was removed from the reflections at the injection point when the string is stopped. In this way, the fundamental is brought down one more octave, which brings the usable range of the stopped notes to a musically more usable register.

Additionally, at the bridge and nut, an adaptive level mechanism is inserted, which prevents the signal in the string from going over a certain level, while at the same time allowing input to come in. If there is input, it is injected, but if there is none, the signal level is kept

[3] http://kyma.symbolicsound.com
[4] http://madronalabs.com/soundplane
[5] https://roli.com/products/seaboard-rise

constant, or slowly growing, depending on the current filter values (affected by many aspects of the playing). In this way, infinite sustain is possible, without sacrificing external resonance and without the risk of feedback explosion.

Since waveguide synthesis is a well-known technique, and the focus of this paper is not on signal processing, I will not go into further detail about the implementation, except when needed in the discussion of the interactions and playing techniques.

Thanks to the high time resolution in the used DSP platform (96kHz for audio signals, 24Hz for control signals), the delay buffers can change size while the string is sounding without generating any artifacts. This means that all parameters of the string model can be dynamically modulated by the interface. For example, while playing, you can change the injection or stopping point, and simultaneously change the degree of stopping.

3.4 Excitation and injection

String models must be injected with energy to produce sound. In basic waveguide models (such as the original Karplus Strong algorithm), this is a often a burst of colored noise. In Living Strings, external sounds captured live by contact microphones on the instrument panel are used to excite the string, both at note onset, and continuously as long as the string is active.

The excitation impulse is taken from the sum of a set of acoustic excitation sources, and is not a predetermined sound grain.
The excitation sources are:

1. Two contact mics on the instrument shell, one on the left side of the top panel, close to the modulation wheel and pitch stick, and the second is fastened to the bottom steel plate on the right side of the instrument.
2. Internal feedback from the instrument's own output (this can be turned off if acoustic feedback is present, since they partly fill the same function of coupling the strings to each other)
3. A bowing mechanism, which generates a pulse train when a finger is moved rapidly along the key

The input from the contact microphones can contain a lot of low frequencies, and since the vibrations sometimes have traveled through various parts of the instrument (the keys and the bottom of the keybed, for example), some sounds are low in high frequency content. Hence, it is pre-processed through a wave-shaping function, based on a simple folding function, to give it more suitable spectral profile. In this way, an adjustable amount of new harmonics are generated without compromising the basic gestural profile and general character of the excitation source. The signal is also high-pass filtered to remove DC components and rumble which can kill the string resonance, if it contains frequencies lower than the tuned delay loop. This is especially important when exciting strings in the upper register.

When a key is pressed, an excitation burst from the incoming signal is injected into the string. It is enveloped with 5ms attack and 65ms decay (although different values have been tested). After the initial excitation, an envelope follower on the incoming signals controls the amount of injected sound into the string. To simplify, when there is none, the string is left alone. When sounds are coming in, the signal in the string is dampened a little, and new signal is injected proportionally.

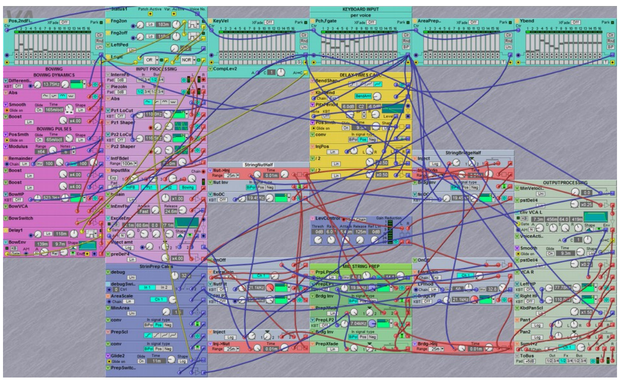

Fig. 2: The string model as implemented in the Nord G2.

3.5 Internal inter-string feedback paths

The string model contains several feedback paths coupling the strings to each other. There is feedback within the digital model, where the complete output is fed back into the injection mechanism of all active strings. There is also feedback from the amplified sound in the room, through vibrations in the steel panels of the keyboard, propagated into the virtual strings through the contact microphones.

3.6 Mapping

The TouchKeys sensors output raw data of up to three touches per key, together with their Y positions, contact areas, and a shared X position. To process this, a custom software was implemented in the free high-level programming tool OSCII-bot[6], specially made for processing OSC and MIDI information. The code implements a voice allocation algorithm, and sends relevant finger data through MIDI CC messages to the voices. Data is filtered to avoid repetitions and minimize MIDI bandwidth. The details of the mapping are explained in a following section.

3.7 Performance mapping

In Living Strings, nothing happens unless a key is pressed. First, we will look at one-finger playing, followed by a description of what happens when several simultaneous fingers are applied to a key.

A key down event opens a string and triggers an excitation burst into the string, scaled by key velocity. For slow key presses, velocity is zero, so it is possible to open a string for resonances and other playing techniques without any excitation.

A key up event starts as an exponential release phase of the string, which is normally about half a second.

The sounding character of a waveguide string is primarily affected by the spectral content of the excitation, and the nature of the filters at the bridge and nut, where the sound wave bounces. These one-pole low-pass filters are controlled globally with the modulation wheel, to fine-tune the character of the instrument. Furthermore, they are affected by other performance parameters.

Increased touch area of the finger raises the filter, making the sound brighter and slowing down the decay of higher partials, and possibly also the whole note. Correspondingly, touching the key with just the tip of the finger, results in a more muted character. Thanks to the adaptive level control mechanism, this can be used to mute and swell a note without re-triggering an excitation.

Increased aftertouch (channel pressure) lowers the bridge and nut low-pass filters, so that the string is muted. Because of the phase response of the filter, this also has the effect of bending the pitch slightly downwards in a characteristic way, much like when muting a guitar string close to the bridge.

The Y position of the finger on the key (in the front to back direction) affects where on the string excitation and injection signals are fed into the waveguide model. The range is from close to the bridge to the midpoint of the string. On a guitar, this would be called the pick position - where the string is plucked. If excited near the bridge, the sound is very bright, the well-known *sul ponticello* character, and near the midpoint of the string, the sound is hollow. These timbral differences are very noticeable when playing, and are caused by wave cancellations when the sound travels through the string in both directions, with different time displacement, resulting in a comb-filtering effect.

The X position of the finger, sideways, controls intonation. E.g., to bend a note slightly upwards, move the finger to the right. This is an absolute mapping, and is not relative to the position of the first

---
[6] http://www.cockos.com/oscii-bot/

touch on the key, which could be slightly safer. Keyboard players are usually not trained to care about where on the key the finger is placed, so to avoid too much unintentional bending, the bend is scaled to give very little response near the middle of the key, with more audible bending towards the left and right edges.

A key can be played with one, two or three fingers at the same time, with different behavior. In the following, I will use the term "top finger" to refer to the finger furthest away from the player.

Moving the top finger back and forth triggers a pulse train, to emulate the effect of bowing on a string. This pulse train is amplified proportionally to the speed of the finger movement and pressure, and the number of pulses is proportional to the distance travelled by the finger. The bowing signal is mixed with the other input signals and injected into the current string. It does not affect other strings. The coarseness and spectral characteristics of the pulse train can be adjusted in the patch. Currently, bowing resulting from movement on higher pitched strings contains less low frequency content.

Bowing can be applied to a silent open string, to initate vibrations, or to inject more energy into already sounding strings.

When two or more fingers touch the key, this has the effect of "stopping" or "preparing" the string with an object, such as a finger or a piece of metal (see Sec. 3.3 for a description of how this is emulated). The top finger decides the position of the stopping, which in this implementation is always the same as the injection position.

The current implementation of the prepared string allows for a continuous transition between a normal open string, over a string lightly stopped with a soft object, to a string stopped completely with a rigid object, acting like a new bridge for two substrings, each consisting of a subsection of the original string. The Y position of the top finger determines the ratio between these substrings. In principle, the key surface serves as a physical map of the virtual string, from the nut to the midpoint of the string. Since a string is symmetric, there is no need to map the whole string, but only one half.

This transition from light to heavy stopping of the string is controlled with the contact surface area of the finger.

The metaphor here is the following: Holding a small, sharp object onto the string results in two substrings. This is similar to holding just the tip of the finger (and possibly the nail) against the key. Pushing the soft, flat part of the fingertip against the key will instead emulate a soft touch, damping the fundamental while retaining frequencies having a node at the touching point. This allows for the playing of harmonics (flageolets) and the creation of resonances based on overtones of key pitches.

It can be argued that a performance metaphor of muting the string would feel more adequate for such playing, since quite some force is required to push a sufficient skin are agains the key. However, inverting the mapping of these two behaviors was found to be equally awkward.

Just like with a real string, the audible results in the middle of the transition (stopping the string half-hard with a half-rigid object) simply results in a muted string, so the mapping from contact area to the stopping parameters is scaled as an S-curve, keeping most of the range within the musically useful far ends of the range, with a sharp transition in the middle.

To provide for further flexibility in playing, the value used for this parameter is the sum of the contact area of the second and third fingers. So, by alternating touch with the thid finger, jumps in this value can be controlled.

In a similar fashion, a third contact finger can be used to cause jumps in the position value (which is decided from the position of the top finger). With the current bowing algorithm, such a jump causes a rapid burst of pulses to be injected into the string, which allows for repeated tremolo-like tap playing.

Playing with two or more fingers on one key is difficult, both motorically, and because the space is small. In some cases, one may want to access stopped strings in faster or polyphonic playing. For this purpose, the left pedal serves as a switch, triggering stopped behavior without the need of a second finger. As before, the top finger position controls stopping/injection point, and the sum of the contact areas on the key is mapped to stopping character, from flageolet to rigid stopping, as before.

All these mappings are active simultaneously, and can be combined. For example, a note can be pitchbent while bowing, and bowing can be applied with one or more fingers on the key.

For all the above behaviors, the general decay characteristics of the strings can be adjusted with the setting of the modulation wheel. In this way, very muted or very bright and resonant strings can quickly be configured. Finger-mapped filter modulations are added on top of this global value.

4 PLAYING TECHNIQUES

The instrument has been used regularly over four months, and some recurring playing techniques have emerged. Further playing techniques may emerge from the continued use of the instrument. One can attempt an exhaustive inventory of possibilities, but because of the inclusion of physical interactions with the keyboard as a physical sounding object, this is also very hard to do.

String excitations can in the simplest case be the actual thump from the key hitting the keybed. One of the contact mics is intentionally placed close to one of the screws connecting the keybed to the panel bottom, so these vibrations are captured well. The instrument shell is a steel panel with a grainy surface suitable for friction sounds such as scratching with nails or finger. Different kinds of knocking and drumming on the panel or the wooden sides also work well. A nail glissando on the keyboard, without depressing the keys, provides an effect very similar to strumming, when injected into open strings.

Button clicks and the springy pitch stick are also good sources for sonic interaction with the virtual strings. The slotted openings for power supply cooling provides a guiro-like excitation when stroked with the nail or a stick. As is evident, it is hard or impossible to do a complete inventory of such playing techniques.

Another technique is to hold certain strings, and excite them with the sounds from other strings. In this way, certain harmonics can be emphasized through resonance.

Thanks to the rich data from the interface, vibrato-like gestures can be applied to almost any parameter of the string model, such as bridge filter, injection point (causing timbral change or pitch change depending on if the string is stopped). Initially silent clusters of strings can be held and used as bank of resonators, approaching a reverb, or be played with subtle scrapings or bowing.

There are to many ways to exploit this interface to be able to mention them all. For examples of a wide range of playing techniques, I refer to the attached video example of an improvised performance on the instrument.

5 DISCUSSION

The main contribution of this instrument is the tight integration of the acoustic and virtual/digital domains, in both directions. This brings back the possibilities of acoustic interactions with the object for the musician, and the vibrations in the instrument body regains their meaning. A lot of hybrid instruments have been developed, but this one is hybrid in the opposite way to what is common – it adds acoustic properties to a digital instrument, instead of vice versa. It adds physical interaction of a different kind to a digital keyboard.

To bring in the complexity and diversity of acoustic sounds as part of the digital instrument greatly enhances the sonic range, gestural expressivity and available playing techniques. Since you can play physically on the panel in infinitely many different ways, it also provides an open-endedness, and source of variation in the hands of the performer. By introducing an open-ended dimension, it imports the complexity of the real world, so hard to emulate in synthesis. It also imparts the material properties of the actual digital instrument on the sound, and manifests the digital instrument as a physical object.

Thanks to the principle of commuted synthesis [11, 12], the characteristic acoustic properties of the casing, as heard while knocking on the panel, is imparted on the string resonances. So, the acoustic properties of the physical keyboard interface really becomes an integrated part of the musical output. Different keyboards will sound different; material and fabrication methods make a difference.

5.1 Expressivity and playability

Over all acoustic instruments, there is a balance between the amount of control over each voice, and the number of voices [15]. This is also present here, and the virtuoso player will use short-cuts and grouped control of several notes at the same time, to reduce cognitive load. Humans are simply not cognitively able to control a high number of parameters for a large number of notes at the same time. Still, the availability of fingertip control when desired is a great feature, which is lacking in most acoustic keyboard instruments, unless you introduce inside playing.

5.2 Repeatability

Sounding strings have complex internal states, so absolute repeatability is in principle not possible. It is also difficult to repeat exactly the same gestural input due to amount of performance dimensions and the small size of the keys. Still, if possible, any gesture and effect can in theory be repeated. There is no randomness, only real-world complexity, which we have spent a lifetime learning to manage. The instrument can be controlled in a quasi-deterministic manner, and it can be most likely be learnt to a degree of virtuosity.

Some features are difficult to control, because of interface shortcomings. For example, finding the exact location of harmonics is difficult because there are no points of reference on the key, and they are distributed over a very short distance on the key surface. Here, a quantization of position information to the approximate positions of the harmonics could help. Still, this should be a soft quantization, allowing some freedom of movement around them, to avoid too perfect and sterile results and limiting the performers control over the sound.

5.3 The sound

The string model can most likely be improved. The focus in the development has so far been on the interaction aspects of the instrument, allowing for an intimate connection between the performer's gesture and the sound. The string synthesis needs to be effective, flexible and good enough. There are a number of physical models of strings, more sophisticated than the one used in this project, e.g., finite difference methods [8] or waveguide meshes [11], and other more fine-grained physical models of an actual string. Such models would allow for interaction with the string in multiple positions at once, which is feasible with the current interface.

Prioritizing between accuracy and fidelity to the modelled natural systems, and the quality of the interaction model, is not easy. From a reseach point of view, both are interesting and important, and worth pursuing. From a musician's perspective, however, without a good interaction model, the instrument will not be fun or rewarding to play. The opposite does not hold, though. With adequate control over the sound, a simple sound source can be the vehicle for good musicianship.

At one point in the development, there was a possibility to play the strings with touch only, without pressing the keys. However, this turned out to be very difficult to control in some situations. It worked well when only touch was used, or when one hand played the keys and the other only used touch. However, it turned out to be hard to mix touch playing with normal keyboard playing, at least within the same hand. It is part of normal keyboard technique to use the sense of touch and the morphology of the keyboard to navigate to the right position. When doing this without touch, you have to rely on eyesight to avoid unintended key activations, which might not be possible when playing difficult passages involving both hands.

6 FUTURE EXTENSIONS AND IMPROVEMENTS

This project is quite new, and there are a number of planned improvements and extensions of the performance mapping that simply have not been implemented yet because of time constraints. Here, I will mention a few of those, as well as some of the more speculative potential extensions.

Traditional keyboard instrument playing relies on multiplicity of notes, and the relations between them regarding timing, dynamics and timbre. The purpose of Living Strings is to extend this to gain more control also over each note. The performer may still want to perform in a more traditional keyboard fashion, triggering a multitude of notes. For this purpose, the left pedal shortcut was introduced, triggering the effect of an extra finger all played keys.

In the same way, a master-key could be assigned, reserved for touch interactions applied to all currently active strings. In this way more complex chords can be controlled as one entity. The plan is to use the lowest key on the current Living Strings keyboard, contra-E, for this purpose. It is an all-white key, with no cutout for a black key, which makes it especially suitable for precise touch interactions.

There are a couple of improvements planned for the bowing mechanism. The dynamics of the bowing should also be modulated by finger contact area, instead of just speed of movement. This would enable repeated playing on flageolets, through short-throw "rubbing" movement around the touch-point, similar to hard bow pressure. If bowing with either first or second finger, instead of as now, only with the top finger. This would allow for a decoupling of stopping point and bowing movement.

Currently, the mapping of finger X position to pitch bend leads to some out-of-tune playing, especially in fast passages. A keyboard player is not trained to care about the position on the key. This can be regarded as a feature, and motivate for further practice, or, one could implement pitch bend based on divergence from first point of contact, so that the note always starts according to equal 12 tone temperament (which may or may not be desired).

A special sustain pedal mechanism is planned, which opens all last active strings (8 voices currently). They will get no direct excitation, but will be open for signal injection from the signal sources. In this way both hands can be used to play, e.g., complex percussive rhythms on the panel.

6.1 Prepared piano

The word "prepared" in prepared piano signifies modifications of the instrument that have been carried out beforehand, allowing for detailed control of pre-prepared strings at design time, but less flexibility during performance, with a focus on traditional keyboard interaction.

On the other hand, "inside piano playing" refers to the practice of using alternative playing techniques directly on the strings and elsewhere in the piano.

Living Strings is more closely related to the latter, thanks to its focus on access to the parameters of string alteration during performance. Still, it would be a quite simple extension to implement a mechanism for preparation of strings, with one or more parameters of the string model decided beforehand, while leaving others for real-time performance. This can, e.g., be done using normal playing combined with a set of switches triggering the storage of certain parameters (injection/stopping position, stopping amount, etc.) and a reset switch that releases all parameters to performance control again. This functionality could easily be expanded upon into presets, alternate tunings, etc., but there are already more sophisticated approaches to such well-controlled synthesis of prepared piano sounds.

In an improvisational context, an easily accessible "preparation" interface could be used to keep and further exploit interesting sounds found while playing, in a manner very similar to the other timbre-focused improvisation instruments I have previously designed, e.g., [1, 15].

6.2 Experimental sound engines

Now, when there is an interaction that works well, it could be fruitful to further develop the Living Strings instrument in a direction away from acoustic metaphors, towards nonlinear behavior, while keeping the rich interaction model. For example, the current model can be modified with experimental bridge-filter types, causing interesting nonlinearities and feedback behaviors. Some initial testing has been done with interesting results. It works quite well, thanks to the adaptive level control mechanism. The string stays at the same level, in spite of feedback. Some initial testing has been done, with interesting results.

In addition to the string engine, a prototype sound engine based on physical models of blown pipes, with gestural control over a number of parameters. Also, an engine based on frequency modulation synthesis has been developed and used in a stage production. These will be published in the near future.

It would also be possible to develop a sound engine based on banks of resonant filters, excited by the current acoustic sources, essentially a version of modal synthesis.

One could consider using alternate interfaces, instead of, or in addition to the TouchKeys enhanced keyboard. For example the idea of a master key for control of all played strings at the same time could be further improved by using a longer ribbon controller, which gives better precision for intonation and harmonics playing.

Two-dimensional multi-touch control surfaces such as Madrona Labs SoundPlane or Haken Continuum [16] could be used with only a slightly altered version of the current mapping, if the surface is divided in a series of strips from left to right, with further playing techniques possible thanks to the larger freedom of sideways movement without physical key boundaries.

Finally, in a related project, instruments have been designed using vocal signals for string excitation and injection. If this is applied to Living Strings performance mapping, complex timbres can be injected while keeping both hands free for keyboard playing.

7 CONCLUSIONS

I have presented a novel hybrid acoustic-digital keyboard instrument based on multi-touch sensors on the keys. The instrument provides extensive control over, and intimate fingertip interaction with, a large number of virtual strings. The acoustic input from the contact microphones, used as the main source of string excitation, provides a richness that is hard to produce with purely synthetic means. The instrument provides a large variety of playing techniques, from traditional keyboard playing down to detailed control over a single string and its resonating properties, through a simple but effective model of prepared strings.

The instrument merges physical modeling synthesis with the acoustic properties of the actual physical keyboard as material object, providing rich mechanical interactions, as well as a complex mapping from multitouch sensors to string synthesis.

The synthesis model is quite simple and can be improved. Still, it is already a satisfying instrument for the able keyboard player, and the addition of multitouch control allows for very dynamic playing, but also requires the musician to practice new kinds of playing techniques, since features such as touch position and finger contact area suddenly have a great impact on the sound.

This is not a substitution for real string instruments, but it provides for new kinds of musical interaction with physical models, through a successful synthesis of the physical and the virtual.

8 ACKNOWLEDGMENTS

Thanks to Chet Singer for some details of the Nord Modular G2 string implementation. The research is supported by the Swedish Research Council.

9 REFERENCES

[1] P. Dahlstedt. Mapping Strategies and Sound Engine Design for an Augmented Hybrid Piano. *Proceedings of NIME*. AMC, 2015.

[2] A. McPherson. TouchKeys: Capacitive Multi-Touch Sensing on a Physical Keyboard. *Proceedings of NIME*. ACM, 2012.

[3] E. Tomás and M. Kaltenbrunner. Tangible Scores: Shaping the Inherent Instrument Score. *Proceedings of NIME*. ACM, 2014.

[4] K. Karplus and A. Strong. Digital synthesis of plucked-string and drum timbres. *Computer Music Journal,* 7.2 (1983), 43-55.

[5] J. O. Smith. Physical modeling using digital waveguides. *Computer Music Journal,* 16.4 (1992), 74-91.

[6] M. Karjalainen, V. Välimäki and T. Tolonen. Plucked-string models: From the Karplus-Strong algorithm to digital waveguides and beyond. *Computer Music Journal*, 22.3 (1998), 17-32.

[7] J. O. Smith. Physical modeling synthesis update. *Computer Music Journal*; 20.2 (1996): 44-56.

[8] S. Bilbao and J. Fitch: Prepared Piano Sound Synthesis. *Proceedings of the 9 th International Digital Audio Effects Conference* (Montreal, Canada), 2006, 77-82.

[9] J. O. Smith. Virtual acoustic musical instruments: Review and update. *Journal of New Music Research*, 33.3 (2004), 283-304.

[10] R. Jones and A. Schloss. Controlling a physical model with a 2D force matrix. *Proceedings of NIME*. ACM, 2007.

[11] M. Karjalainen, V. Välimäki and Z. Jánosy. *Towards high-quality sound synthesis of the guitar and string instruments*. *Proceedings of the International Computer Music Conference*. ICMA, 1993.

[12] J. O. Smith III. Efficient synthesis of stringed musical instruments. *Proceedings of the International Computer Music Conference*. ICMA, 1993.

[13] Smith, Hazel, and Roger Dean, eds. Practice-led research, research-led practice in the creative arts. Edinburgh University Press, 2009.

[14] P. Dahlstedt. Expert Commentary: Turning the Piano Keyboard Inside Out. A.R. Jensenius, M.J. Lyons (Eds.): *A NIME Reader: Fifteen Years of New Interfaces for Musical Expression.* Springer, 2017, 430–432.

[15] P. Dahlstedt. Dynamic Mapping Strategies for Expressive Synthesis Performance and Improvisation. *Lecture Notes in Computer Science*, 5493, Springer, 2009, 227–242.

[16] L. Haken, R. Abdullah, and M. Smart. The continuum: a continuous music keyboard. *Proceedings of the International Computer Music Conference*. ICMA, 1992.