Mapping Strategies and Sound Engine Design for an Augmented Hybrid Piano

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ABSTRACT

Based on a combination of novel mapping techniques and carefully designed sound engines, I present an augmented hybrid piano specifically designed for improvisation. The mapping technique, originally developed for other control interfaces but here adapted to the piano keyboard, is based on a dynamic vectorization of control parameters, allowing both wild sonic exploration and minute intimate expression. The original piano sound is used as the sole sound source, subjected to processing techniques such as virtual resonance strings, dynamic buffer shuffling, and acoustic and virtual feedback. Thanks to speaker and microphone placement, the acoustic and processed sounds interact in both directions and blend into one new instrument. This also allows for unorthodox playing (knocking, plucking, shouting). Processing parameters are controlled from the keyboard playing alone, allowing intuitive control of complex processing by ear, integrating expressive musical playing with sonic exploration. The instrument is not random, but somewhat unpredictable. This feeds into the improvisation, defining a particular idiomatics of the instruments. Hence, the instrument itself is an essential part of the musical work. Performances include concerts in UK, Japan, Singapore, Australia and Sweden, in solos and ensembles, performed by several pianists. Variations of this hybrid instrument for digital keyboards are also presented.

Author Keywords

augmented instrument, piano, keyboard, mapping, hybrid instrument, performance, improvisation

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

During the last few years I have run a research project with the goal to design electronic instruments for free improvisation meeting the following criteria: 1) They should be free of presets, but with an easily operated mechanism for real time exploration of the space of possible sounds. 2) There should be a correlation between physical effort and sound production, and a change in gestural input should correspond to a change in sonic gestural output. 3) They should be as direct and free in the interaction as acoustic instruments are, and the user should be able to develop a skill and musicianship over time.

This project has resulted in a family of synthesis-based instruments using various interfaces and playing styles, e.g. instruments using arrays of pressure sensors, percussion controllers (pitched and non-pitched), MIDI keyboards [1] and even the GuitarHero controller [3]. The main break-through in this project has been the introduction of an unconventional mapping approach, where the control parameters are dynamically mapped to initially randomized vectors in synthesis parameter space. The vector system can be re-scaled and shifted on the fly, by ear, allowing for control of complex explorations and trajectories in a high dimensional space.

In this paper, a particular development within this project is described: *Foldings*, an implementation of a hybrid piano instrument, integrating the acoustic sound of the grand piano with processed sound from the same source. The processing is controlled by the pianist's playing on the keyboard, through the aforementioned vectorization algorithm. The electronic sounds are projected from speakers right behind the piano, causing the two sounds domains to merge into a new hybrid instrument that behaves organically. It also responds well to non-piano sounds, such as knocks on the wood, shouts into the piano, preparations or other inside-the-piano playing techniques.

1.1 Background and previous art

It is natural for musicians and composers to push the limits of their instruments, trying to extend the sound and performance possibilities. This is often done in collaboration with the instrument maker (e.g., as throughout the development of the modern piano, with involvement of J.S. and J.C. Bach, Beethoven, Liszt, Alkan and many other pianists), and new techniques that are initially perceived as an abuse of the instrument may later be encouraged and enhanced, or even explicitly supported, in a newer version of the instrument. But as the design of the piano has not changed much during the last century, composers have turned to extended techniques (playing inside the piano, directly on the strings or on the wooden parts), preparations with physical objects so that the strings, although played in normal ways, sound like completely new instruments — inharmonic, percussive, noisy or bell-like — as pioneered by John Cage. Later, composers added pre-recorded sounds to the piano sound, or modified the acoustic sounds through electronic means, as in, e.g. Stockhausen's Kontakte (with prerecorded tape part complementing the acoustic piano and percussion) and Mantra (using sine wave ring modulation on live piano sounds).

The current repertoire for piano and live electronics is

Figure 1: A picture from the premiere of the Foldings system in 2011. The red machine on top of the grand piano is the Nord G2 signal processing engine. It does both mapping and sound processing, but is not interacted with directly during the performance. Later performances have used a smaller version without interface, hidden behind the performer. The Moog Piano Bar MIDI sensor can be seen on top of the keys, against the keyboard lid.

huge (see [11] for an extensive list). External processing is often controlled through a separate interface (sliders, knobs, computer with mouse) by the player or an electronic musician. Many piano improvisers and performers (such as Sten Sandell and Chris Brown) have added various pieces of electronics to the piano to extend its timbral range.

What I wanted to design here, was instead an instrument where such external interfaces and ad hoc effects were not necessary, with timbral control integrated with the normal playing. Also, I wanted no time-line, no presets, nor any predetermined ongoing processes. The instrument should always be ready for whatever is needed musically.

Related work has been done by Andrew McPherson, but the other way around [6, 8]. He has constructed a piano where the physical strings are excited by virtual oscillators and synthesized signals controlled by external machinery, to provide the pianist with extended performance possibilities, while my system excites virtual strings and other processing mechanisms with sounds from the piano.

To get precise information about key presses, either the Moog Piano Bar sensor or a Yamaha Disklavier player piano have been used, which both provide MIDI output of keyboard, velocity and pedal information. Foldings can also be set up using a digital keyboard as sound source, where keyboard information through MIDI is generally available. This solution has been used during theater productions and improvisation tours, where a grand piano has not been available. Since this allows for the use of other keyboard sounds as source material for the processing, such as celesta or harpsichord, and independent control of the source volume, it also has turned into a slightly different hybrid instrument, with its own set of possibilities and idioms. Both versions will be discussed in this paper. They have also been used together.

1.2 A practiced-based approach

This project stems from an urge to extend the expression of the piano in an improvisational setting. It also aims to take advantage of performance motor skills from years of keyboard training, applied to new timbres, and the expressive musical skills acquired through many years of musicianship. The method I usually apply is the following: Based on an artistic need or desire, experiment with a number of prototypes to try to fulfill it. Refine the best prototype into a working instrument, and evaluate this in real artistic use over long time, solo and with other musicians. Observe emerging idiomatics (characteristic playing patterns), recurring devices and exploitations of particularities of the implementation, and do a qualitative evaluation based on musical experience with the instrument, and skill development. Also, study resulting musical interactions with other musicians on traditional instruments; do I match their proven nuances and agility. And how does it compare to playing a regular piano? This is not a quantitative evaluation of the playability of the instrument. It involves the my own experiences as the designer and performer of the instrument, as well as one other very experienced pianist. The analysis made, and the statements about the instrument, are not opinions (even though they by nature are subjective), but an attempt at accessing the detailed and rich experience and knowledge that the performer builds up over several years of playing this specific new instrument, in the light of the particular knowledge of the instrument designer, who in this case is the same person. This kind of long-term evaluation is rarely done with NIME instruments, but quantitative lab tests can hardly tell us if an instrument works out there, with expert co-players, in front of an audience. This kind of research is not about saying ”this instrument is better than that one”, but about investigating what is possible to do, in which ways we can construct instruments, and how we can understand the resulting music and musical interplay in the light of the original intentions, technically and aesthetically.

2. TOOL USER AND TOOL MAKER

The concept of an augmented instrument initiates a discussion about the relationship between the tool user and the tool, mediated through the tool and the use there-of. The creation of any artwork is influenced by the available tools, as described by, e.g., Dahlstedt in his theory of artistic creative process [2]. Learning a tool creates pathways in the mind, which in turn influences our imagination. We do not think freely, but rather in terms of what is possible, based on our cognitive models and experience of certain tools. An altered instrument provides new possibilities, and necessarily has aesthetic implications. When the tool becomes more powerful, e.g., by providing generative and computational abilities, the relationship between tool user and tool maker becomes more entangled, also from an authorship point of view. Depending on how the generative properties are implemented, and what degree of control the performer has over them, the results can either have a conforming effect (all results sound similar, independent on who uses it), or a widening of the space of the possible (the tool takes you to new points in a search space provided by the medium you work in, and provides new strategies to explore it).

Xenia Pestova provides an extensive analysis of the relation between the musician and the instrument in her thesis [12], discussing different models for interaction: score following, score orientation and the “live electronic pianist”. This latter category is further divided into different control scenarios: the pianist using external interfaces or external keyboard to control the electronics, and the possible need of an extra live-electronics musician. Pestova’s discussion, however, is focused on the notion of composition, where the work has a beginning and end. On the contrary, this work is oriented toward the idea of an instrument, for use in either solo or ensemble performance. So we need to add the category of an *augmented piano* to Pestova’s list, where the playing is free, where there is no time-line, and it feels like a new instrument to play. It is essentially open-ended.

Such an augmented instrument can then be used in improvisation as well as composition. The Foldings system has been used in both ways, by several performers, although the primary intended use is in free or structured improvisation.

There is, however, an interesting aspect in the situation when the composer-musician is designing the instrument himself. He or she integrates many aesthetic choices and constraints in the design of the instrument, essentially embedding his aesthetic preferences in its construction. These design choices affect the playing, the possibilities and the potential musical outcome, as these built-in constraints resonate with the musical aesthetics of the player. In this case, depending on how strong the aesthetic constraints are, the instrument itself can be regarded as the work of art, equal to a composition. The output is different on micro level, but has a perceivable identity in structure and character, directly emerging from the instrument design. This position is argued for by Swedish researcher and improviser Per Anders Nilsson [10]. When performing solo on Foldings, I think of it as performing a specific work, even if the music is improvised. Certain ways of interacting with the instrument are more rewarding than others, and during development and rehearsals I have developed a specific way of playing each variation of the instrument (same mapping mechanism, different sound engines), and even given a name to each sound engine, regarding them as "movements" in a larger work.

In the case when the instrument is not designed by the player, the situation is slightly different. The aesthetic constraints built into the instrument and those provided by the player are not the same, which might lead to a different musical output when these interact. This other musician might choose to exploit other interaction patterns and playing techniques based on his aesthetic preferences, resulting in very different music, which could be surprising to the original designer of the instrument. This is exactly what happened when, in a research workshop in 2011, the Foldings instrument was presented to the senior contemporary music interpreter and improviser John Tilbury[1]. He approached it with an open mind, and started to explore how it responded to his way of playing, exploiting a specific "corner" of the space of the possible – the very soft, subtle and micro-tonal subspace.

The space of the possible has a scope defined by what is possible to do with the instrument, and a topology, i.e., a structure of proximity, neighborhood and ways to traverse it. The topology is also defined by the instrument, since this is the very vehicle for navigation of the space. A tool defines a topological network of the space of the theoretically possible in the chosen medium (in this case sound). The non-toolmaker musician (Tilbury) transcended not the space defined by the instrument designer, but the part of the space that was known and envisioned by the designer. As humans we have limited cognitive capacity, and we cannot visualize internally the huge spaces of possibilities defined by a generative mechanism of such complexity as a musical instrument. Or in other words, Tilbury went beyond my cognitive model of the instrument, and explored ways to use it that I had not predicted, not only discovering unknown parts of the sound and structure space, but also exploring them along axes that I was unaware of.

It can be argued that the mere possibility of such a transcendence, that the instrument goes beyond the instrument designer's predictive capacity, is an indication that the instrument has potential to surprise its maker and its users, and that it can serve as a sufficiently complex vehicle for the presentation and development of musical ideas by himself and other users for a long time. On a more humorous note, it could also be argued that it is just a sign of the maker's limited visualization capacity, but I do hope this is not the case here.

The issue of finding somebody else who wants to learn and play a novel instrument, and to build a community around it, has been further analyzed by McPherson and Kim [9]. In their case study, based around a set of commissions for their augmented magnetic resonator piano, they found not only that different composers approach the instrument in very different ways, but also that a redesign of the instrument was needed, primarily relaxing the constraints and making it more open-ended, which resonates well with my observations.

3. DESIGN

The technology behind Foldings is as follows: A MIDI-enabled grand piano, four microphones, a signal processor (Nord Modular G2) with custom software, and two speakers behind the piano. In minimal settings it has been performed with only a stereo microphone and one full-range monitor under the piano.

The software system consists of a mapping engine translating from keyboard control parameters to processing and synthesis parameters, and a set of sound engines. Two engines have primarily been used during concert performances: a micro-tonal adaptive resonator and an adaptive buffer shuffler. Both rely on the sound of the piano, and the sound of the keyboard mechanism and the surroundings. The electronic sound is projected from speakers behind the piano, hence going back into the instrument, providing a truly hybrid acoustic-electric instrument. For example, the virtual resonance strings provided by one of the engine allows for sophisticated play with resonances using knocks on the piano lid or shouts into the piano.

3.1 Mapping technique

The mapping development started in 2005, with keyboard-based synthesis instruments with separate timbres for each key, and timbral morphing between keys using the pitch bend controller. It was called *the prepared synth*, inspired by Cage's prepared piano, and allowed for complex timbral variation and control, while keeping the keyboard pitch mapping. It was implemented as an array of eight synthesis parameter values per key. This was followed by a more general approach, developed in 2006-2012 [4, 1], where each control element (pad or key) is mapped to a vector in synthesis parameter space. The vectors are scaled by control magnitudes (pad pressure, key velocity, controller tilt, etc., depending on interface), and when several control elements (pads, keys) are activated at the same time, the resulting scaled vectors are summed into a result vector, pointing to a specific point in synthesis parameter space. This point represents a specific synthesis parameter set, and hence, corresponds to a specific sonic results. Internal states of the sound engine can complicate the correspondence between synthesis parameters and the sounding result, but the general idea is the same.

This mapping engine has been applied to a set of different interfaces. A piano keyboard implementation provided specific challenges. For example, it was discovered that for percussion and keyboard applications, the vector-based approach was inadequate, since all soft notes would sound almost the same (the vectors are too short to make a difference). Instead, a gravity model was developed, based on the vector model but with an added normalization step, so that each pressed key corresponds to a point in synthesis

[1]See **video example 1**, from a concert following the workshop.

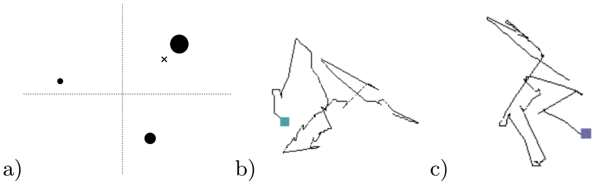

Figure 2: a) An illustration of the gravity model. When several notes, each corresponding to a point in synthesis parameter space, are played with different velocities, they attain different gravities. A louder note will have a larger attraction effect on the resulting point (the small cross). This illustration is greatly simplified. In the real system, the gravities vary over time, following attack, decay and release settings, and the process takes place in an 8 or 16-dimensional parameter space. Fig. b) and c) show 2D projections of real trajectories (each of 10 sec duration), taken from video example 4, where also the simultaneous control of 8 parameters can be seen and heard.

parameter space. Each point has an attraction strength, a gravity, that is scaled by key velocity. If two keys are played simultaneously with similar velocity, the resulting point is in the middle between them. If one of the two is played harder, the resulting point will be closer to this one. This gravity amount is controlled by a traditional ADSR envelope (attack, decay, sustain, release). Adjusting the shape of the ADSR, different playing behaviors can be achieved. For example, if the release time is long, the gravity will persist for a while, affecting the timbre for some time after the key was released. Also, these gravity envelopes can be accumulated – playing the same key repeatedly increases its gravity.

The spread of the gravity point set can be scaled globally, enabling exploration of large parts of the synthesis space, or fine-tuned intimate expression. If an interesting point in synthesis parameter space is found, the whole point set can be shifted to this point. Then, all gravity points will be centered around this new origin, and the subspace surrounding it can be explored. Combined with a reduction of point set scaling, this provides a means to zoom in on interesting timbral regions, or to just alter the general timbre at will, by ear. The origin can be re-shifted, or reset to the real origin at any time.

Another challenge posed by the keyboard version of the mapping was polyphony. In the previous applications, the sound is monophonic, controlled by a large number of identical control elements (pressure pads, switches, drum pads, etc.). This choice was based on observation of how acoustic instruments are designed – there seems to be an inverse correlation between the number of continuous degrees of sonic freedom (timbre, dynamic and pitch) and the number of simultaneous possible sounds. For example, think of church organ, piano, guitar, violin and wind instruments. They represent a falling scale with respect to polyphony, but a rising scale of sonic expressivity *per voice*. This is probably based on the limited cognitive and motor capacity of the human performer. However, when applying this mapping approach to a keyboard instrument, polyphonic playing was a necessity, simply because pianistic playing is based on it, and the system is based on a real piano. The solution was to use a single set of processing parameters on all voices, creating an instrument that has a single, variable timbre, instantiated in several polyphonic voices with controllable pitch.

The mapping is an all-to-all mapping, since each control parameter affects all synthesis parameters, up or down. Research has shown that parameter coupling, inspired by how acoustic instruments work, is easier to play and perceived as more expressive [5]. This idea is here taken to an extreme. Larger velocities have more effect, and when a chord is played, all keys affect the timbre.

The point set of the gravity engine is not designed, but randomized at design time, i.e., not during playing. The number of parameters is too large to set manually, and this approach enables exploration of the space of possible sounds without constraints. The mapping engine is technically comparable to an interactive one-parent genetic algorithm, with aural evaluation of offspring, and the added possibility to audition interpolated combinations of different offspring (this comparison is further discussed in [4]).

The output coordinates/parameters of the mapping engine can be mapped arbitrarily to synthesis parameters, since they all show the same kind of behavior. Hence, this mapping engine can be applied to almost any sound engine.

The externally controllable parameters of the mapping engine are: Gravity envelope attack/decay/sustain/release, and point set scaling.

3.2 Sound engines

The Foldings system currently consists of three sound engines, with quite different sonic results. Two of them have been used extensively in solo and ensemble performances, while the third has only been used in ensembles. They are all controlled by a similar mapping engine, but with totally different parameter sets.

3.2.1 The Ballad engine

This engine is based around the idea of acoustic resonance. Each pressed piano key instantiates a corresponding virtual string (a tuned delay line with adjustable filtering, hence a variation on the Karplus-Strong algorithm), which is fed an initial sound-burst from the microphone nearest to the corresponding real string. Note that this is a compound sound, possibly resulting from other simultaneously pressed keys, from already sounding strings, or from other sounds. In this way, the virtual string can sound in different ways depending on musical context. There are external controls (not processed by the mapping engine) that affects The envelope characteristics of the virtual string are controlled directly by external controls (MIDI sliders) or set initially. It uses an adaptive feedback control, and is hence capable of infinite sustain, but it can also be set to decay as a normal string. As long as it sounds, it is also fed an adjustable amount of direct sound from the microphones, with adaptive control, creating audible resonances and changes in timbres, while keeping the sounding energy at a constant level. To blur the very definite pitch of the piano, each virtual string is detuned by an amount controlled from the mapping engine. The scaling of the detuning can be set globally, allowing for micro-tonal playing, glissandi, stepped pitch variation of held notes, micro-tonal trills, etc., depending on gravity envelope settings.

To further complicate the sound and provide some texture, the sound engine contains a modulated delay side chain, fed back into the virtual string model as faint transformed echoes. The amount of this effect, as well as all timbral parameters of the sound engine (delay times, delay feed amount, return modulation amounts, filter parameters, etc.) are mapped to parameters from the mapping engine, and are hence affected by every aspect of the keyboard playing, providing a very dynamic and varied performance instrument[2].

Externally controlled parameters of the Ballad engine are: amplitude envelope attack/decay/sustain/release, sound injection amount (for held notes), and initial sound injection length (for virtual string excitation).

3.2.2 The Shuffle engine

This sound engine is based around a continuous circular buffer of a few seconds. Input-wise, it acts as an adaptive looper, i.e., the loop is always running, and as soon as there is sound into the microphones, it records. If the incoming sound is soft, it keeps a little of the previous sound, but if the incoming sound is loud, it replaces the previous sound completely. The sound from the circular buffer is played back based on parameters from the mapping engine, controlling starting position, loop length and playback speed (including negative speeds). In this way, the sonic result can be transposed drastically. Very short loops can sound like metallic notes, and long loops become rhythmic gestures. Because of the specific nature of the loop playback parameters, the gravity envelope of the mapping engine is simplified to an on-off gate function to avoid excessive glissandi. Also, because radical transposition of rich digital sound can create very strong treble content, a bandpass filter is included, which tracks the played key on the piano. This provides a more controlled spectral output. The width of the bandpass filter can be adjusted down to self-resonance, providing a wide range of sonic behavior.

The most interesting feature of this sound engine is the fact that while the keyboard playing affects the looper playback parameters, the very same played notes also produce a sound and hence enter the loop. There is no way to decouple the contents of the looper from the control of the looper playback. This takes a while to get used to, but it provides very interesting input to the improvisation, and almost gives the illusion of improvising with a second performer[3].

3.2.3 The Feedback engine

This sound engine is based on a complex feedback network involving a set of interconnected comb filters (pitched one-cycle delays), a set of effect blocks (frequency shifter, delay, phaser and a multimode filter), all connected in a matrix with separate weights at each node. Feedback strengths and routings are controlled by parameters from the mapping engine. The feedback network is injected with sound from the piano at the start of the note, but the timbres emerging from the feedback network quickly take over, and there is little room for the continued injection of the acoustic sounds into a held note. The timbre is varied, and alters based on the keyboard playing, with musically interesting phase transitions occurring with drastic parameter changes. However, real-time control is not as evident as with the other sound engines. It does not feel as organic as the them, since the influence of the acoustic sound is less prominent and quickly vanishes. It feels more like a synthesized instrument. Because of this, it has mostly been used in ensemble playing. Still, it has an acoustic feel due to the acoustic source instrument sounds[4].

3.2.4 Digital keyboards as source and controller

For practical reasons, digital pianos have also been used, primarily due to the unavailability of a grand piano in some performance venues, but it quickly turned into a feature. With a digital keyboard, different keyboard sounds can be used as source sounds. The setup is the same, and it is still a hybrid instrument: The "normal" keyboard sound from the digital piano goes into the same sound engines as in the acoustic version. Hence, the relationship between a "normal" keyboard sound and the processed sound is the same, even though the original sound is a digital imitation. Since grand pianos rarely sound good through stage speakers, celesta and harpsichord have often been used, but also bells and organs. These timbres work very well the Ballad engine.

When performing on a digital keyboard, the volume of the "acoustic" source sound can be controlled independently, and even be muted. When playing only the processed sounds in this way, the instrument is radically transformed. It becomes a very expressive electronic instrument that feels very acoustic, thanks to the underlying source sound and the virtual acoustic resonances.

To provide for even more acoustic interaction, a microphone has sometimes been taped to the lid of the digital keyboard, and mixed into the source keyboard sound, to allow for knocks, voice sounds and other non-instrumental sounds to go into the resonant strings of the Ballad engine, or into the looping buffer of the Shuffle engine, in the same way as such sounds can be used with a real grand piano.

4. PLAYING TECHNIQUES

During extensive rehearsals, performances and recordings, characteristic playing techniques have emerged for the different sound engines.

In the ballad engine, a core technique is to hold a chord or a note, and inject short bursts of staccato sound into the virtual resonance strings, or knocks on the wooden piano lid, causing abrupt changes in timbre, sounding very much like acoustic resonances. This can be further elaborated into textures of quick altering between legato and staccato playing, overlapping in both hands.

Adjusting the gravity envelope times to very short durations, which enable abrupt changes in mapped parameters, it is possible to produce micro-tonal trills and minute timbral variations. This is done by holding one or more keys and playing another key repeatedly. Since each played key introduces a change in all mapped parameters, the sound is altered. When the key is released, the parameters go back to their previous value. Larger rapid timbral transitions can also be effective.

Controlled glissando gestures, very novel in a piano context, can be produced in different ways, for example as detuning of the virtual string affected by a decaying gravity point. With accumulation of several gravity envelopes, through repeated playing of the same key, further complex glissando gestures can be produced.

Repeated playing of notes or sequences, in tremolo patterns or on a single note, can be used to provide a kind of drifting navigation in the parameter space. This requires that the gravity envelopes are rather slow, and that the point set scaling is low, so that each key does not have too much effect, avoiding large jumps at the note attacks.

Using a digital keyboard as source and controller, peculiar swells can be produced. If the source keyboard sound is taken through a volume pedal before it reaches the sound engine, the source sound can be muted. Then, a *ff* chord can be played muted, and when the volume pedal is raised, the decaying chord, now audible, causes resonances in the virtual strings, resulting in an eerie, distant swell.

With the Shuffle engine, the player can exploit the interdependency of the keyboard as controller and as sound source in many ways. One example is to alter between between filling the loop and exploiting it. Even though it is of

[2]See **video example 2** and **sound example 1**
[3]See **sound example 2**.
[4]It is used by the left pianist in **video example 3**.

course always filled, the performer can concentrate on one role at a time.

When an interesting repetitive sonic texture is found, is can be kept by holding the keys and only using quite soft playing, slightly altering the looping parameters without injecting too much new sound into the looping buffer. The held texture can also be interrupted by loud single presses on another key, causing an abrupt change in the playback, but going back when the key is released, possibly with slightly altered buffer contents.

Since playback speed is one of the mapped parameters, the performer can sometimes exploit this as a velocity-to-pitch effect, allowing bouncing gestures and melodic playing on a single key. This requires that another key or other keys are held, so that the velocity of the extra added key maps proportionally to the playback speed through the mapping engine.

5. DISCUSSION

The unpredictability of this instrument evokes a certain kind of interaction. It feels like chasing a moving target. You react to the aural consequences of your playing, and your reaction causes a semi-unpredictable effect, which is then causing further reaction, etc. Still, the performer has expressive control over dynamics and pitch, and a range of repeatable playing techniques at her disposal. But there is a certain unpredictable component, which in some cases, especially with the Shuffle engine, feels like you are playing with another human musician. The instrument in itself, or rather the emergent musical structures, provides impulses for further playing. These patterns of impulses given by the musician and the impulses returned from the instrument results in a particular idiomatics. In a sense, the instrument is a composition, with very clear identity, and it invites you to play in a certain way. This aspect of an electronic instrument embodying a set of aesthetic preferences of its designer has been discussed in depth by Nilsson [10].

The instruments have been evaluated qualitatively through extensive playing in many different contexts, by different performers, over several years, in performances all over the world (including the UK, Japan, Singapore, Australia and Sweden). In total, it has so far been used in 35 public concerts/performances in very different contexts. The Foldings instrument has been used together with many diverse instruments, such as percussion, saxophone, and Japanese Noh-flute with its peculiar non-harmonic overtone series and micro-tonal phrases. It has also been used to accompany dance performers in a semi-composed setting, and overall it has turned out to be a very versatile and universal instrument capable of diverse range of output. Maybe the best test was a tour in Sweden and UK together with the legendary improvisation ensemble AMM, where two out of four players played different versions of the Foldings system, and a third player played the *exPressure Pad* (the electronic improvisation instrument for which the vector mapping was originally developed [1]).

5.1 Future development

A larger number of voices in the sound engines is needed. This would allow for slower, more dynamic navigation of the parameter space, through the use of large numbers of keyboard events. New sound engines will be developed, as well as improvements of the existing ones. As previously described, the Feedback sound engine is not really satisfying yet, and it needs to become more acoustic in its behavior.

A pitch class version has been considered, where each pitch class (c, d, e, etc.) is mapped to the same point in processing space, regardless of octave. Then, harmonic playing and the use of tonal patterns in different octaves would be easier to manage.

The mapping engine will be tested with enhanced keyboard sensing, such as McPherson's key surface sensors, providing pressure and position data [7]. This work has started, both with acoustic and digital pianos.

6. CONCLUSIONS

The Foldings system has proven a successful merge of an acoustic and electronic instrument, allowing the the performer to use established keyboard performance techniques together with advanced electronic processing, without alternative controllers or distracting laptops screens between the musician and the audience. The novel mapping engine together with the different hybrid sound engines provide for a number of novel performance techniques, greatly extending the timbral range of the piano, without sacrificing its original qualities. Still, the instrument, because it indeed feels like a new instrument, behaves organically and responsively, and is rewarding to play.

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