Augmenting the Acoustic Piano with Electromagnetic String Actuation and Continuous Key Position Sensing

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ABSTRACT

This paper presents the magnetic resonator piano, an augmented instrument enhancing the capabilities of the acoustic grand piano. Electromagnetic actuators induce the strings to vibration, allowing each note to be continuously controlled in amplitude, frequency, and timbre without external loudspeakers. Feedback from a single pickup on the piano soundboard allows the actuator waveforms to remain locked in phase with the natural motion of each string. We also present an augmented piano keyboard which reports the continuous position of every key. Time and spatial resolution are sufficient to capture detailed data about key press, release, pretouch, aftertouch, and other extended gestures. The system, which is designed with cost and setup constraints in mind, seeks to give pianists continuous control over the musical sound of their instrument. The instrument has been used in concert performances, with the electronically-actuated sounds blending with acoustic instruments naturally and without amplification.

Keywords

Augmented instruments, piano, interfaces, electromagnetic actuation, gesture measurement

1. INTRODUCTION

The acoustic piano is among the most versatile of instruments, capable of complex polyphony and rapid passagework across an extremely wide register. Yet in comparison with most other acoustic instruments, the piano has a surprising limitation: once a note is struck, the performer has virtually no ability to modulate its sound before it is released. Building a keyboard instrument with the ability to continuously shape each note is an age-old problem: In the 15th century, Leonardo da Vinci devised an instrument using rosined wheels to selectively sound a bank of strings; later, the late 18th and early 19th centuries saw a proliferation of new instruments attempting to bring indefinite sustain and continuous modulation to the keyboard [6].

With modern electronic synthesizers, infinite sustain and real-time note shaping are no longer challenging. Yet despite decades of improvement, many performers find that electronic instruments still do not match the richness and nuance of their acoustic counterparts; very few pianists would choose even the most sophisticated synthetic piano over any acoustic grand of reasonable quality.

This paper presents the magnetic resonator piano, which seeks to unify the flexibility of synthesis with the richness of the acoustic piano by electronically augmenting an acoustic grand piano. Electromagnetic actuators directly induce the strings to vibration, bypassing the piano's percussive hammer mechanism and allowing continuous control over the sound of each note. Continuous position sensing of each piano key allows the performer to control parameters of actuation in real time without impeding traditional piano technique, while an optional second keyboard can be used to control the actuators without engaging the mechanical action. All sound is produced by the piano strings, without loudspeakers, facilitating integration with other acoustic instruments in a concert hall. Vocabulary of this hybrid acoustic-electronic instrument includes indefinite sustain, crescendos from silence, harmonics on each piano string, and new timbres which combine the warmth and resonance of the acoustic piano with an ethereal purity often associated with electronic synthesis.

2. PREVIOUS WORK

Electromagnetic piano string actuation has been recently explored by Bloland, Berdahl et al. [1, 3]. Their system, the Electromagnetically-Prepared Piano, uses twelve solenoid magnets placed over selected strings. Signals are generated in Max/MSP and can include periodic waveforms, filtered noise, and prerecorded samples. The resulting sounds are quite compelling, blending the warmth of the piano with a uniquely electronic purity.

Electronic actuation has also been applied to the electric guitar, both in commercial technologies such as the EBow [9] and using more comprehensive feedback approaches [2]. Work by Boutin and Besnainou explores active control of a violin bridge [5] and xylophone bar [4]. Stable active control of acoustic mechanisms requires very low processing latency, and is often accomplished using specialized digital signal processing hardware. Dozio and Mantegazza [7] provide guidance for the implementation of real-time control systems using general-purpose microprocessors; Lee et al. [10] present one such system achieving latency as low as $24\mu s$ at a 40kHz sampling rate.

Separately, keyboard controllers have been developed which report the continuous position of each key. Freed and Avizienis [8] demonstrate a keyboard capable of continuous key position sensing, including high-speed communication with a host computer to transmit high-bandwidth position data. A keyboard controller by Moog [12] also permits horizontal

NIME2010, 15-18th June 2010, Sydney, Australia

motion of each key and touch sensitivity on the key surface. These interfaces build on established keyboard technique to allow control of more complex musical processes.

2.1 Comparison with Previous Work

Our electromagnetic actuation system operates on the same principle as the Electromagnetically-Prepared Piano [1], but we present an implementation which allows coverage of the entire range of the piano at reasonable cost. We also employ a feedback-based control strategy that can be implemented without the requirement of ultra low latency or separate pickups for each string. In comparison to efforts which focus on actuation or keyboard sensing in isolation, we seek to tightly integrate both elements deeply into the piano, fusing traditional (hammer-actuated) piano technique and electronic control into a single augmented instrument that acts as a natural extension of the acoustic piano.

3. ELECTROMAGNETIC ACTUATION

The design of the actuator system is explained in detail in an article currently in press [11]. The major features of the hardware and software design are outlined below.

3.1 Hardware Design

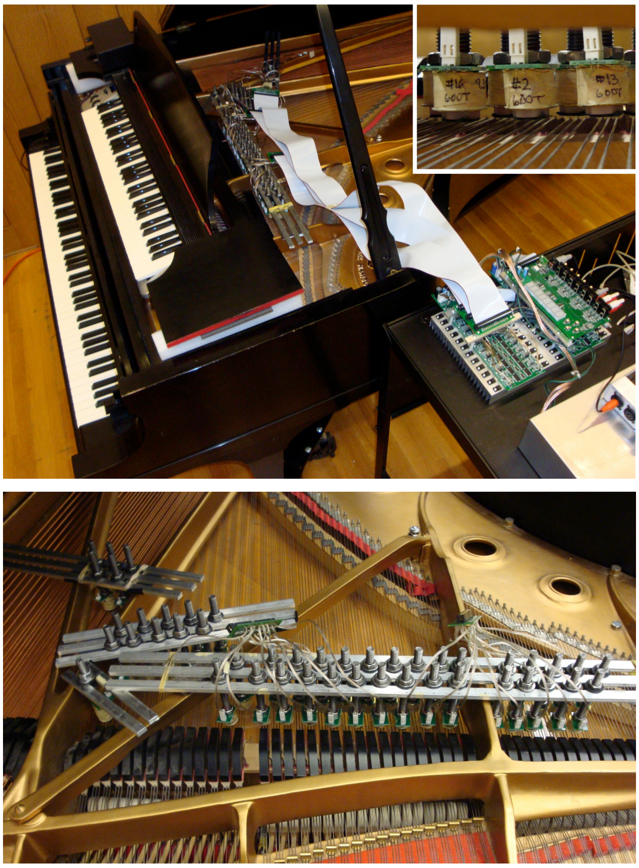

Figure 1: The magnetic resonator piano. Top: complete system. Top inset: electromagnetic actuators above the strings. Bottom: Brackets holding actuators for four octaves of strings.

Figure 1 shows a picture of the electromagnetic actuation system, which can be installed in any acoustic grand piano without modification to the instrument. A block diagram is shown in Figure 2. Actuation works on the principle of ferromagnetic attraction, whose application to piano strings is detailed in [1]. One custom-wound solenoid electromagnet is used for each note of the piano, up to 88 notes total (48 in the current prototype). Actuators are suspended above the string by an aluminum bracket which rests on the steel beams of the piano frame. Though the actuators must initially be adjusted to the specific geometry of a piano, removal and reinstallation are as simple as lifting and replacing the aluminum brackets.

Each actuator is driven by a dedicated amplifier optimized for low cost and parts count. Amplifier input signals are generated by computer, but it would be prohibitively expensive to use a separate DAC channel for each note of the piano. Instead, each amplifier input is attached to a 16-channel multiplexer which dynamically selects an available DAC channel. A microcontroller maintains a mapping from DAC channels to amplifiers, receiving MIDI Control Change messages to make and break connections. In this way, 88 actuators can be covered using an inexpensive commercial audio interface, with the maximum polyphony determined by the number of DAC channels.

3.2 Signal Processing

The strongest tones are obtained when the actuator waveform remains locked in phase to the motion of the string. On the other hand, recording the motion of each string faces several obstacles, including EM interference from the electromagnets and substantial digital buffering delays which make precise feedback control impossible[1].

We have developed an intermediate approach which uses a single piezo pickup on the piano soundboard to record the sum of all string vibrations. Bandpass filters isolate the fundamental frequency of each note (or, optionally, the first several harmonics). These filtered signals drive phase-locked loops which synthesize new waveforms that remain in phase with the filtered signal (Figure 3). Mechanical delays and digital buffering produce a phase lag between the motion of the string at the point of its interaction with the actuator and the pickup signal. This lag is unknown but time-invariant; therefore, the PLL includes an adjustable phase offset $\Delta\phi$, calibrated by ear, which allows the actuator signal to remain precisely locked in phase with the motion of each string.

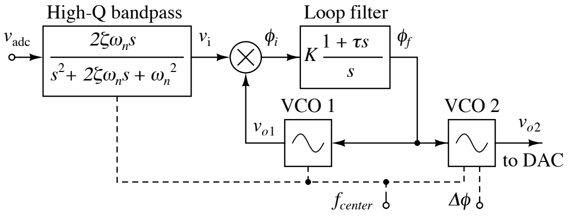

Figure 3: Input filter and PLL system for one active note.

3.3 Measurements

A piano string can be induced to vibration at any of its harmonics (and very weakly in between), with response falling off with increasing frequency due to actuator inductance and mechanical losses. Figure 4 compares the amplitude of electromagnetic and hammer-actuated tones on middle C (C4). Electronically-actuated tones show comparable amplitude to standard piano notes, but with a slower

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[1] Deploying the ultra-low latency feedback systems of Section 2 on a scale to cover the entire piano would face substantial hurdles in cost and complexity.

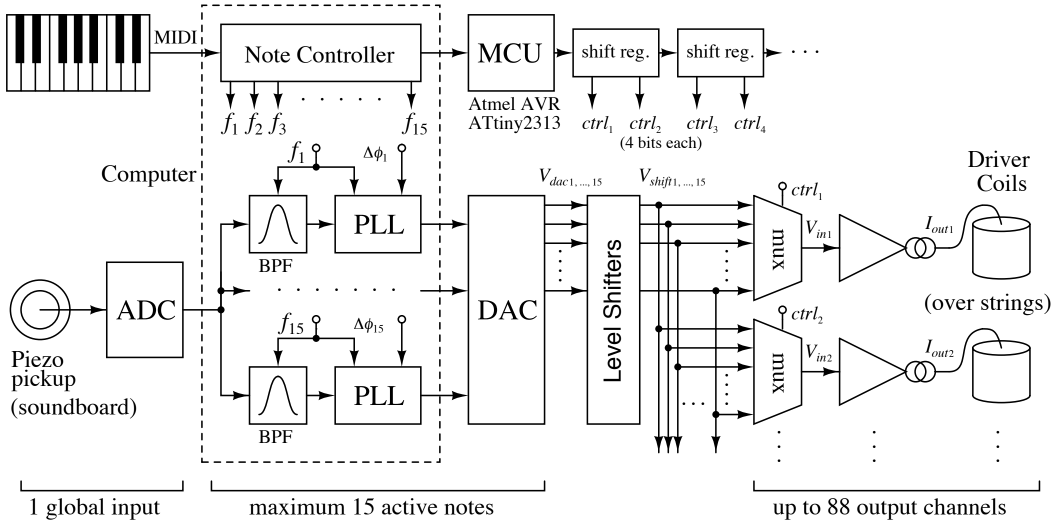

Figure 2: Block diagram of the magnetic resonator piano.

attack time and extended sustain[2]. Figure 4 also shows that the use of feedback produces stronger, more consistent tones.

Musically speaking, electromagnetic tones exhibit a pure, ethereal tone quality that remains mellow even at loud dynamics. The musical qualities reflect their spectral content (Figure 5) which, in comparison to the piano, emphasizes the fundamental frequency but contains less energy in the higher partials. Figure 5 shows that a variety of spectra (and correspondingly, a variety of timbres) can be generated by varying the harmonic content of the actuator waveform, though limited high-frequency performance of the electromagnets makes replication of brighter piano timbres difficult. Future work will explore amplifier and electromagnet designs with stronger high-frequency performance.

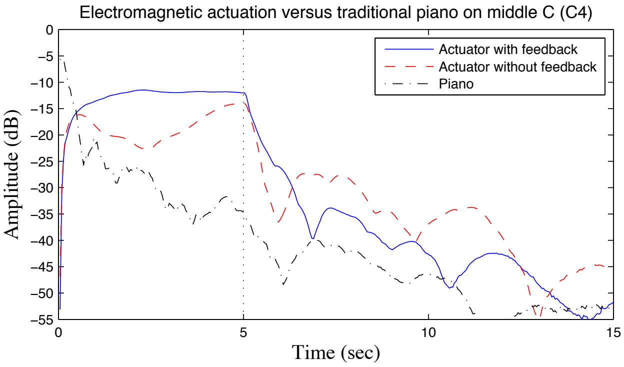

Figure 4: Amplitude of electromagnetic actuation on middle C (C4) versus a piano note played approximately *forte*. Actuator tones last 5 seconds.

3.4 Control Parameters

The actuator system is not merely a source of new sounds. Its principal goal is to provide the performer with a means of continuously shaping the sound of the piano. It is important, then, to highlight the controllable parameters of each actuator:

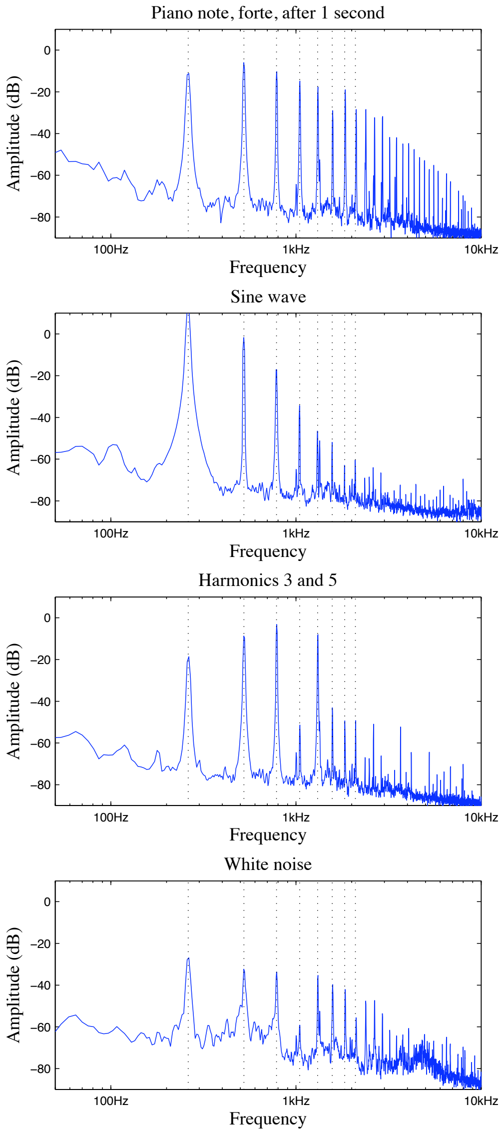

Figure 5: Spectra for actuation with several waveforms compared with a standard piano note, C4.

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[2] Figure 4 shows the result of driving the string at constant amplitude. Arbitrary dynamic envelopes are possible by varying the amplitude of the actuator signal.

- Amplitude (and amplitude envelope)
- Frequency (relative to string fundamental)
- Phase (relative to existing string motion)
- Spectrum (harmonic content plus noise sources)

Together, these parameters define the *musical* vocabulary of the instrument, including dynamics, articulation, timbre and tone quality. Correlations between acoustic features and subjective musical attributes are often difficult to quantify, and are nearly always more subtle than simple one-to-one mappings (e.g. amplitude to dynamic, frequency to pitch, etc.). Ultimately, the human performer should have the ability to shape the instrument's acoustic parameters to his or her taste. To that end, we have created a new performance interface which intuitively extends the keyboard to allow continuous expression.

4. CONTINUOUS KEYBOARD SENSING

Mechanically, the piano offers very few dimensions of control: the only aspect of keyboard performance that affects the sound is the velocity with which a hammer strikes a string. On the other hand, pianists describe their instrument in far richer terms, discussing a wide palette of tone colors and sometimes swearing by gestures that would seem to have little acoustic relevance, including angle of approach to the keyboard or force on the keys after note onset. We hypothesize, then, that pianists transmit much more expressive data to the instrument than a simple onset-release approach would reveal (or a MIDI controller would record). Capturing this additional expressive data has exciting potential to modulate the sound of the piano in a musically intuitive manner.

4.1 Hardware Design

We have developed an interface which continuously records key position on the acoustic piano using a modified Moog Piano Bar [13]. The Piano Bar uses optical reflectance sensors on each white key and interruption sensors on each black key (Figure 6). Though it was developed as a MIDI controller, internal pads on the circuit board provide access to the continuous analog light levels for each key. 88 sensors are multiplexed over 12 lines such that white keys can be measured at a rate of 600Hz and black keys at 1.8kHz. A digital signal provides a falling edge at the beginning of each cycle of keys, allowing synchronized data capture.

Our data capture system uses two 6-channel, 12-bit ADCs [15] attached to an Atmel AVR microcontroller [14] which behaves as a USB audio device. Data is transmitted in a raw, packed 12-bit format and decoded by the host computer to extract the position of each key. The system is calibrated after installation, recording minimum and maximum values on each key to compensate for variations in sensitivity and mechanical sensor position.

4.2 Measurements

Figure 7 shows a short excerpt recorded on a Steinway D grand piano with continuous key position sensing, demonstrating several important points:

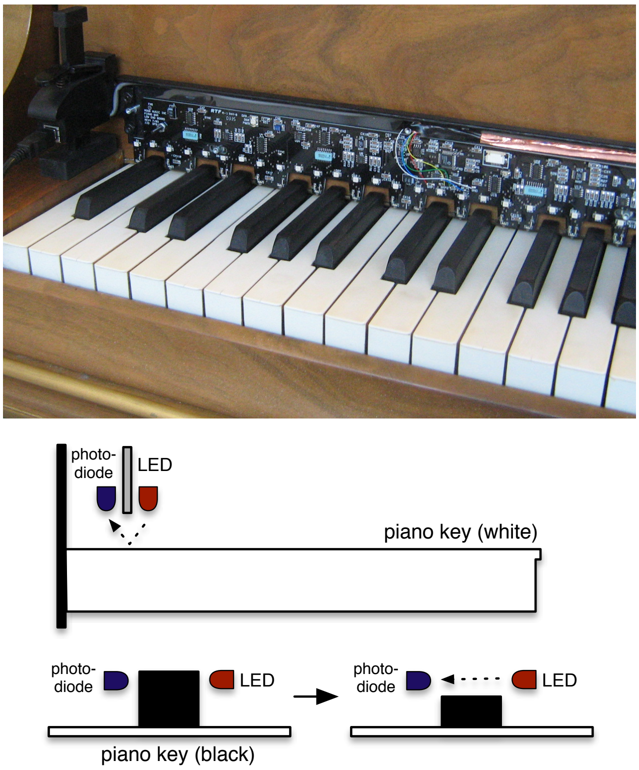

Figure 6: Disassembled view of Moog Piano Bar showing optical sensors, and diagram of sensor operation.

1. The sampling rate is sufficient to capture several points during the short interval of a key press. MIDI velocity can thus be calculated (as the Piano Bar does internally), but the *shape* of key press events can also be measured, which may suggest specific types of performance technique. Key release can be measured in a similar manner. As an example, Figure 8 shows the continuous velocity of each key for an excerpt of Figure 7.
2. Force on the keys after onset creates a compression of the felt pads underneath the keyboard, resulting in slight key displacement. In particular, the long note (F4) in Figure 7 shows a decreasing force over the course of the note.
3. Partial key-press gestures (either intentional or inadvertent) which do not create a sound are recorded.
4. Properties of the keyboard itself are revealed, including mechanical ringing on key release resulting from an underdamped system.

This sensor system can be used to study traditional piano technique at new levels of detail. Equally compelling, though, is its ability to capture a range of extended keyboard gestures, each of which can be mapped to distinct actuator behavior:

- Deliberate aftertouch and vibrato
- Pre-touch and partial key presses
- Very slow, controlled motion of each key
- Light sweeps across the keyboard
- Lifting and shaking keys between thumb and forefinger

Figure 9 shows an example of several of these gestures performed on a single key.

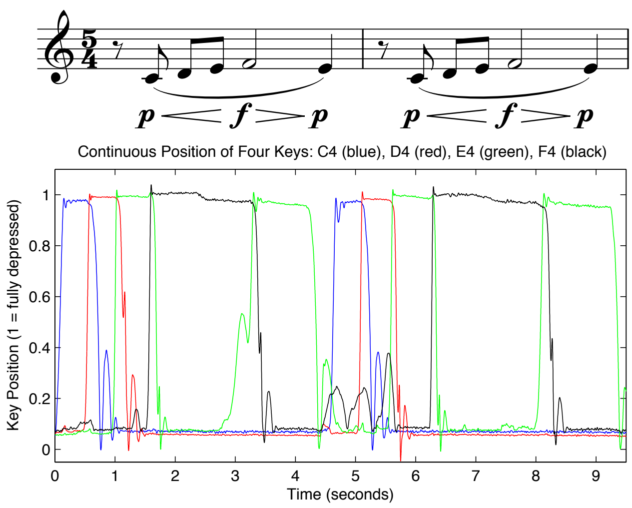

Figure 7: Continuous position of four keys for a short musical phrase.

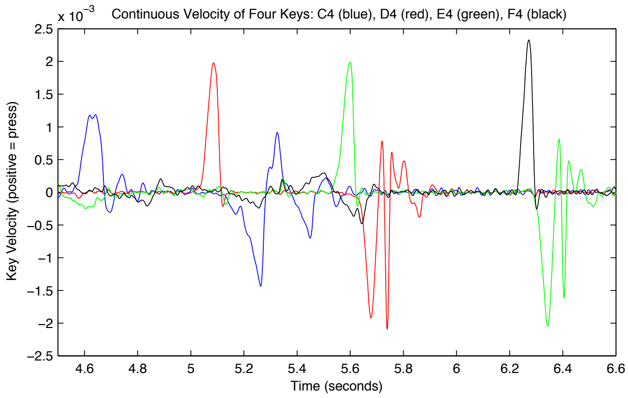

Figure 8: Continuous key velocity for excerpt of previous figure.

5. MUSICAL IMPLICATIONS

The preceding sections demonstrate augmentation of both interface and sound production aspects of the piano. To create a truly expressive musical instrument, data from the keyboard must be mapped in a meaningful way to parameters of string actuation. The following sections discuss past experiences and future directions.

5.1 Concert Performance

The magnetic resonator piano was used in a concert performance November 2009 in Philadelphia, featuring music composed for it by Andrew McPherson [3]. Two pieces were performed: *Secrets of Antikythera*, which was performed by a single pianist on magnetic resonator piano, and *d'Amore*, which employed pitch tracking on a viola soloist to selectively induce vibrations in the piano strings, creating a resonant harmonic glow behind the viola.

This concert predated the continuous keyboard sensor. Instead, in *Secrets of Antikythera*, two keyboards were used to control the actuators: the piano keyboard with a Moog Piano Bar and a secondary MIDI keyboard (see Figure 1), which was used in situations where hammer action was undesirable. Timbres and time-varying parameters were programmed in advance and selected like MIDI programs. Although this arrangement falls short of the goal of continuous performer control, the instrument was nonetheless easily playable by the pianist, and the resulting sounds blended naturally with both traditional piano and viola. Electromagnetically-actuated sounds were particularly effective in quieter, sparser sections employing the pedal, where the piano resonance could be explored without its customary percussive character. [11] provides further reflection on this concert.

5.2 Implications of Continuous Sensing

The continuous keyboard sensing described in Section 4 profoundly changes the performance experience. On nearly every keyboard instrument, regardless of the dynamic level, complete key presses are required to produce sound. Deriving performance data from subtle variations in key position gives rise to a new technique based on light touch, freeing the fingers from fully engaging the comparably heavy mechanical lever system. Nonetheless, even small deflections of the keys provide haptic feedback to the performer. Passages of great delicacy and rapidity can be played without engaging the hammers, and it is straightforward to transition between light technique and standard piano playing.

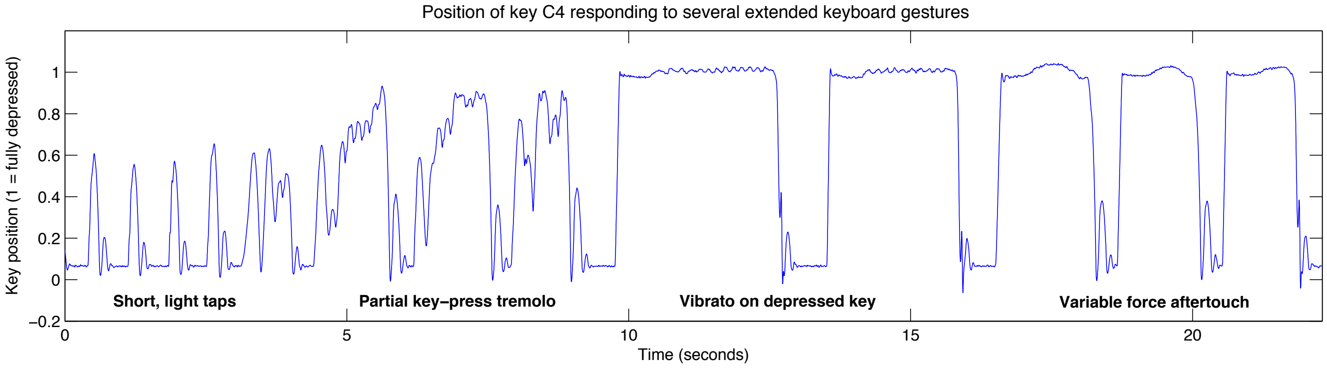

Figure 9: Continuous position measurement of several extended keyboard gestures.

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[3] A demonstration video can be found at: `http://www.youtube.com/watch?v=WDTaH_d8s8c`

The secondary MIDI keyboard, when used, presents a more traditional performance experience, since it is not equipped with continuous sensing. (It would be possible, of course, to use an enhanced controller like the Moog Multiply-Touch-Sensitive Keyboard [12] in its place.) The controller software seamlessly handles simultaneous performance on both keyboards, the only constraint being the need to physically lift the piano dampers with the pedal in order to effectively use the upper keyboard.

5.3 Gesture-Sound Mapping

The potential for completely new keyboard techniques is exciting, but we also aim to develop approaches which augment existing piano technique, building on the extensive training of skilled pianists. Ongoing work explores mappings between gestural data and sound production. These quantities are inherently coupled in acoustic instruments, and maintaining the illusion of tight coupling is critical to producing an expressive electronic instrument. Tight coupling requires both low latency and design choices that align with the performer's physical intuition. For example, heavy force on the keys should correlate with stronger sounds, vibrato actions should result in acoustic vibrato effects, and light key touches should produce soft, airy sounds.

We plan to explore these couplings in collaboration with pianists. First, we intend to use continuous key sensing to study traditional piano performance in greater detail, identifying common physical gestures and their correlation with the performer's expressive intent. Second, we will use lessons learned from this study to generate mappings from sensor data to sound production that extend the possibilities of the piano in an intuitive manner, soliciting feedback from performers on the perceived expressivity of each choice of mapping.

5.4 Final Remarks

The magnetic resonator piano opens up new creative opportunities for both pianists and composers by allowing control of the piano sound both within and across notes. Design decisions were made with cost and setup efficiency in mind, resulting in a system which is installable in any grand piano and controllable with standard computer hardware. We look forward to future collaborations with composers and performers to fully explore the musical potential of this instrument.

6. ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant # 0937060 to the Computing Research Association for the CIFellows Project.

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