The Sparksichord: Practical Implementation of a Lorentz Force Electromagnetic Actuation and Feedback System

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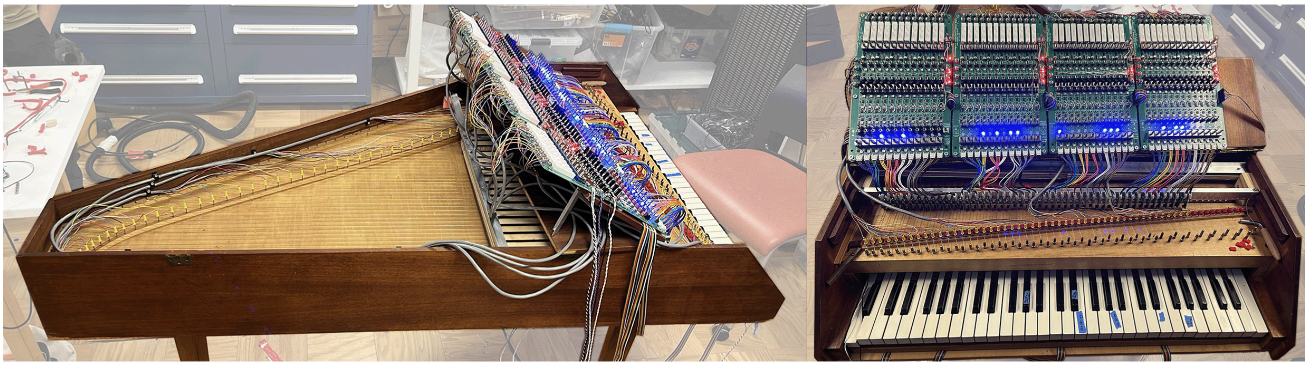

Figure 1: The Sparksichord

Abstract

In line with a sustained community interest in electromagnetic actuation of musical instruments, we describe practical considerations for Lorentz Force actuation in conductive strings, exemplified by the Sparksichord – an augmented harpsichord that uses Lorentz Force actuation, optical feedback, and analog circuitry to sustain vibrations of its brass strings. Electromagnetically-actuated and feedback instruments have grown increasingly popular in NIME, though most systems rely on the use of solenoid-style electromagnetic coils. By running current through the string itself, Lorentz Force actuation offers an alternate arrangement of magnets and wire that can afford new modes of interaction, a broader frequency response, and cheaper implementation. We aim to empower practitioners with a toolbox for designing and building actuated instruments of this style and describe our specific implementation for this instrument.

Keywords

Electromagnetic actuation, sustain, augmented instruments, analog circuits, optical sensing

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1 Introduction

A persistent topic of interest in digital musical instrument (DMI) research is the creation of hybrid acoustic-electronic instruments based on actuating (i.e. inducing vibrations in) musical instrument strings, membranes, air columns, or other resonant elements [15, 23, 32]. Actuating physical systems rather than producing purely synthetic sound offers a range of novel sonic and tactile effects, while also potentially exposing the sound-producing apparatus for direct manipulation by the performer. Strings are perhaps the most thoroughly explored of these actuated elements. The predominant actuation approach in both research and commercial practice involves the use of solenoid-style (cylindrical) electromagnetic coils driving strings made from steel or other ferromagnetic materials.

This paper develops the theory and practice of a different approach to electromagnetic string actuation, building on earlier foundations in the literature [24]. The approach, commonly known as *Lorentz Force actuation*, involves an alternate arrangement of magnets, wire, and strings in which the string itself becomes the primary electrical conductor. Although the arrangement has been described before in patents and papers [20, 24], little documentation for realized musical systems exists. It is most notably used in Alvin Lucier's *Music on a Long Thin Wire* [22] and has most recently been described within NIME by Schmidt & Gurevich [35].

Lorentz Force actuation is less explored than coil-based actuation in the realm of musical instruments, perhaps because of the extensive documentation surrounding coil-actuated projects by hobbyists and professional practitioners alike, though as this paper will show, both approaches can be relatively simple to implement with easily available parts. Lorentz Force actuation and coil-based actuation are not always interchangeable for a given instrument, and the two approaches have different advantages and limitations. This paper aims to provide a practical introduction to Lorentz Force actuation, illustrating its musical utility through a case study of the *Sparksichord*, a harpsichord with 48 self-sustaining strings using a fully analog configuration of Lorentz Force actuation and optical vibration sensing.

2 Background

2.1 Related Work

Over the past decade, the NIME community has seen new works and discourse surrounding electromagnetic actuation and/or feedback musical instruments. Many of these developments and discussions describe implementations of electromagnetic actuation, most of which utilize coil-transducer style actuation. Coil-based augmentations largely fall into three categories; (1) using an electromagnet to drive a ferrous sound-making element with a solenoid coil [19, 20, 23], (2) using an electromagnet to drive a permanent magnet attached to a non-ferrous sound-making element with a solenoid coil [1, 10], or (3) using a transducer mounted to an instrument body to indirectly vibrate the sound-making elements through acoustic or mechanical coupling [18, 26, 31, 34, 37]. Other methods of actuation and feedback that do not rely on electromagnetic coils nor Lorentz Force actuation to excite a sound-generating element are also possible (i.e., piezo-element actuation [9]) but less common.

Keyboard instruments have been of particular interest to electromagnetic actuation practitioners, with documentation of an electromagnetically-actuated piano dating back to the 19th century [13]. Some more recent works actuate their strings or tonebars by driving strings or magnets with synthesized tones, as does the Magnetic Resonator Piano [23], Electromagnetically-prepared piano [7], and the EMVibe [10], with some practitioners experimenting with more tightly-controlled forms of feedback to achieve infinite-sustain as done in the Electromagnetically Sustained Rhodes piano [36]. Though many of these actuated instruments don't require the player to be in direct physical contact with the vibrating element, many newer actuated instruments actually necessitate it, introducing a new paradigm of inherently haptic instruments that rely on chaotic, unpredictable feedback that foster a greater sense of agency from the instrument [11, 15, 18, 26, 28, 30, 34, 35, 38].

In the past couple years, we have seen a number of new commercial developments utilizing electromagnetic actuation (other than the renowned eBow [19]), such as Korg Berlin's Electro-Acoustic Synth[1] and SoundStone's String Armonica[2], as well as DIY and hobbyist efforts to share open-source knowledge and designs for sustainer systems[3], suggesting an ever-growing interest in these instruments that extends beyond academia.

2.2 Electromagnetic Actuation Overview

2.2.1 Transducers: Sensors & Actuators.

Transducers are devices that convert one form of energy into another. For example, microphones are a form of transducer that first converts acoustic energy into mechanical energy, and then mechanical energy to electrical signals. These can be thought of as 'sensors'. Conversely, speakers use electrical energy to induce mechanical motion in an element and consequently generate acoustic pressure, and can generally be thought of as 'actuators'. Dynamic-coil microphones and loudspeakers are two common examples of coil-based sensors and actuators (respectively), and they work via the principles of electromagnetic induction.

For example, as you speak into a microphone, the acoustic pressure generated by your vocal cords excites a thin diaphragm with many windings of copper wire (called the voice-coil) attached. This diaphragm and coil pair vibrates with this excitement near a permanent magnet such that the coil is subject to a changing magnetic field, which in turn induces an alternating electric current in the coil per the laws of magnetic induction and proportional to the diaphragm was subject to. This phenomenon also works in reverse, as in the case of a dynamic coil speaker; applying an alternating electric current to a voice-coil near a permanent magnetic field induces vibration in the coil and diaphragm pair, and in turn creates audible acoustic pressure. In either case, the strength of electromagnetic induction scales linearly with the number of turns of wire in the voice coil, increasing signal strength while keeping things physically compact.

2.2.2 Lorentz Force Sensing and Actuation.

Now one can imagine a special case of this voice coil and permanent magnet combination where the coil is unwound (number of turns = 1) and stretched out but still nearby the permanent magnet; electromagnetic principles are still in play such that moving the wire nearby the magnet will induce a voltage across the wire, and running an electric current through the wire will induce a force on the wire. The force felt by the wire is known as the Lorentz Force, and is the namesake of this actuation method. The former case – vibrating a string in a magnetic field – is well documented as a string-sensing method by scientists and practitioners [33] and is even available commercially as a pickup method for classical stringed instruments[4].

2.2.3 Sustaining, Damping, and Transformations.

The ever-popular eBow device [19] popularized a musical effect probably most well known as 'infinite sustain'. This device, when held close to a vibrating steel guitar string, uses the principles of electromagnetics to add energy to the string in such a way that its vibrations are sustained indefinitely (Figure 2). The fundamental requirements for a feedback infinite-sustain system are (a) a sensor, (b) an actuator, and (c) a closed-loop gain between the sensing and actuating methods that adds enough energy to the system to allow vibrational energy to accumulate. Without sufficient gain, the sustain of an instrument may be increased or augmented but will eventually fade out.

To augment the natural resonances of the sound-making element – in most cases a metal string – this feedback system needs to do more than simply add energy; extensive effort has gone into exploring the active damping of sound-making elements – a significantly more complex challenge than infinite sustain [3, 4, 40]. To achieve effective damping, phase coherence between the sensor and actuator is required to remain stable across the desired audio bandwidth [6, 20]. Achieving phase coherence has been explored in a few different manners: ultra-low latency processing where the time delay is negligible; with additional processing to add a correction delay [7, 8]; and collocated or nearly-collocated sensing and actuation [6, 20]. Additionally, strings vibrate on two axes while most sensors and actuators only interact with a single

[1] https://www.youtube.com/watch?v=wpsXy8z0RGA
[2] https://www.youtube.com/watch?v=5mOhg0gz9DI
[3] https://bitbucket.org/metalmarshmallow/mm-diy-sustainer/src/main/
[4] https://www.stringamp.com/

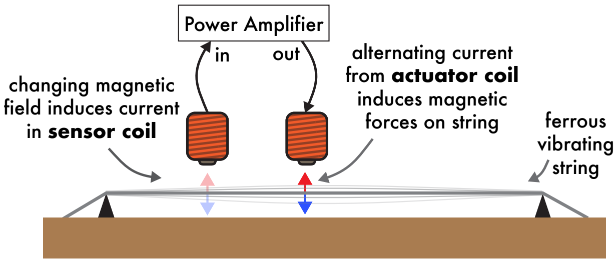

Figure 2: Simplified block diagram of EM Coil Sustaining, as is done in eBows

axis, thus requiring the use of multi-axis sensing and actuation to offer the most responsive control as explored by [20] and [4].

Research efforts have also explored the active transformation of the feedback loop, allowing a system to alter harmonic content and timbre, sometimes to the point of making a convincing imitation of a synthesized tone or acoustic instrument. For example, a string may be driven such that the harmonics present in the string emulate that of a triangle wave or flute [3, 5, 20, 21], or harmonics may be altered to vibrate at frequencies they do not naturally resonate at [9].

Electromagnetic coil sensing and actuating are well-documented and the most common method for achieving sustained vibrations, though feedback control is far from limited to coils; Optical, Magnetic, and piezoelectric transducers can fill the role of sensing, while Lorentz Force Actuation or piezoelectric transducers can be used to actuate.

3 Technical Implementation of Lorentz Force Actuation

This section contains an explanation of each aspect of a practical implementation of open-loop Lorentz Force Actuation, closed-loop infinite sustain, and higher-order control of a string. The cumulative force felt by a charged particle exposed to electric and magnetic fields is known as the *Lorentz Force*. A special case of the Lorentz Force (sometimes referred to as the *Laplace Force*) describes the magnetic force felt by a current-carrying wire exposed to a magnetic field:

$$\mathbf{F} = I\mathbf{L} \times \mathbf{B} \qquad (1)$$

where $\mathbf{F}$ is the force vector felt by the wire, I is the current through the wire, $\mathbf{B}$ is the magnetic field vector, and $\mathbf{L}$ is the length of the wire exposed to the magnetic field.

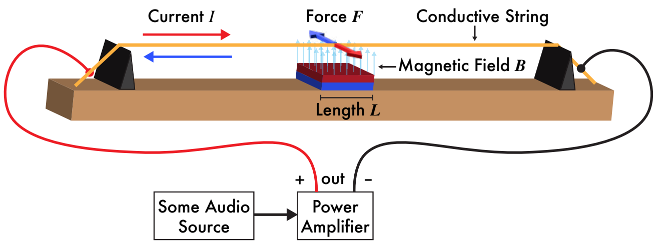

Figure 3: Lorentz Force Overview

3.1 Open-Loop String Actuation

3.1.1 Power Amplifier.
A power amplifier takes a relatively small electric signal and amplifies it to a sufficient level to drive an element such as a speaker coil. A powered device like this is typically designed to drive the copper coils wound within a speaker, but as in Alvin Lucier's *Music on a Long Thin Wire* [22], they can also be used to drive a tensioned, conductive string (Figure 3). The power amplifier modulates the value of current I in equation 1.

3.1.2 Permanent Magnets and their placement.
As seen in equation 1, the magnitude of force $\mathbf{F}$ on a string at any given moment is proportional to the current I through the string, the strength of the magnetic field $\mathbf{B}$ from the permanent magnet, and the length of the string in the field $\mathbf{L}$. In the context of an actuated string, this intuitively suggests that the stronger pull-force a magnet has, the stronger the actuation force and the louder the string vibrates. Similarly, the higher the current through the string, the louder the string vibrates.

The strength and timbre of actuation is highly dependent on the placement of the permanent magnet. In the case of open-loop actuation where an arbitrary signal is applied to the string, the analogy of guitar or harpsichord plucking position is useful. That is, the closer to the center of the vibrating portion of the string is plucked, the more prominent the fundamental frequency and lower harmonics of the string are, and the closer to the termination point (nut or bridge) the string is plucked, the more emphasis on the higher harmonics. Likewise, placing the magnet towards the center of the string favors the fundamental frequency and lower harmonics of the string, whereas placement towards the nut or bridge emphasizes higher harmonics.

3.1.3 Open Loop Actuation, String Resistivity, & Heat Buildup.
Putting these ingredients together, it is possible to drive a string with an oscillator tuned to match the string's frequency. In fact, this is the premise of Hanson, Anderson, and Macomber's 1994 experiment investigating nonlinearities in harpsichord string dynamics [17]. However, depending on the material properties of the string, some of the actuation current may be dissipated as heat in the string's internal resistance, introducing thermal expansion of the string and causing it to lengthen and reduce its tension. This brings the frequency of the string down causing it to no longer match the frequency of the open-loop actuation signal [24].

The resistivity of some conductive metals is shown in Figure 4 [5]. Metals such as yellow and red brass are much less resistive than iron and steel, which means they are more robust to string detuning. It should be noted, however, that heat treatment or work-hardening of the string material affects resistance [2, 12], where annealed metals will typically have higher conductivity than hardened metals. Heat-treating or other processes that increase the strength of a metal string are often required for strings to withstand the tensions typically found in musical instruments, so it is fair to assume any wire intended for stringing instruments will have slightly greater resistivity than in Figure 4.

[5] https://www.effectrode.com/knowledge-base/conductivity-of-metals-sorted-by-resistivity/

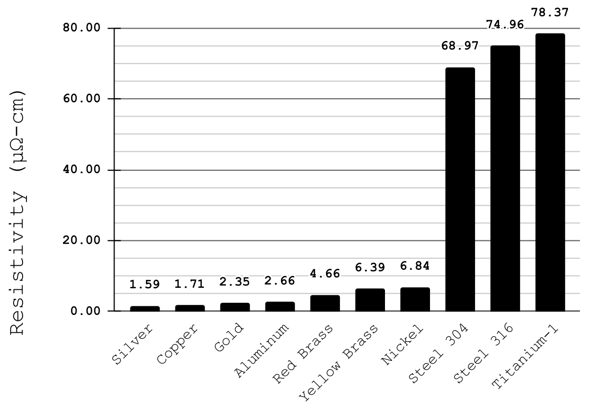

Figure 4: Resistivity of conductive materials used in musical instrument strings (as reported by the CSNDT dataset by Eddy Current Technology Incorporated)

The intensity of detuning is proportional to its heat buildup and therefore proportional to the resistivity inherent to the string:

$$Q = I^2Rt$$

where Q = heat buildup, I = electric current, R = resistance, and t = time. Though this formula suggests that the string may heat up and continue to detune indefinitely as electric current is applied, there is an element of heat dissipation into the surrounding air and any other materials the string is in contact with[6]. In other words, for a real system, the detuning effect from heat buildup eventually finds equilibrium with the heat dissipation, stabilizing the tuning for a given electric current at a given room temperature.

To minimize the effects of string detuning, the following recommendations are made:

- **Minimize resistivity of the string**: Highly conductive materials such as brass will be more resilient to thermal detuning. Thicker diameter wire of the same material allows for a larger cross-sectional area, also increasing conductivity.
- **Minimize the current through the string**: Though this will yield a lower actuation force on its own, a similar actuation force can be achieved by bringing the permanent magnet closer to the string or using a stronger permanent magnet to increase **B**. However, also note that the center of string has a wider displacement than near its termination points, meaning a magnet can only get so close before buzzing.
- Or, if infinite sustain is the goal, then **introduce closed-loop feedback** as outlined in the following section.

3.2 Closed-Loop String Actuation

If one's goal is to sustain vibrations of the string, a form of closed-loop feedback can be implemented to improve actuation efficiency and create a sustain that is robust to pitch change by sensing the string's own vibration and using that signal for actuation. The following section outlines practical considerations for such a system.

[6]It should be noted that for the relatively low-power (5 Watt, 1 Amp maximum) systems explored in this paper, a given string's heat buildup was usually imperceptible to the touch and posed no apparent danger to the musicians, strings, or instruments involved.

3.2.1 String Vibration Sensing.

To achieve an infinitely-sustaining feedback system, some method of sensing the string's vibration is required. Probably the most popular method for sensing string vibrations is an electromagnetic coil such as a guitar pickup. However, as mentioned previously, this method of sensing is only applicable to ferrous strings such as iron and steel because pickups rely on the magnetizability of the sensed string. For non-ferrous strings, other sensing methods are possible. For example, a piezo pickup could be used to sense a string's force [4, 16], or an optical pickup can be used to sense the string's position [4, 17, 35?] as seen in Figure 5.

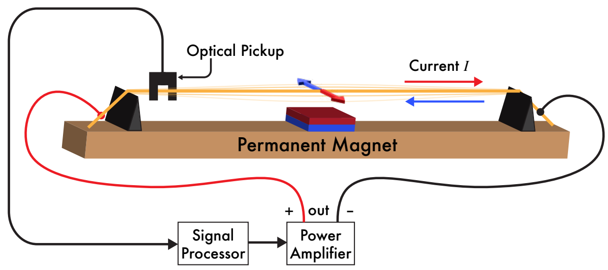

Figure 5: Example of a Lorentz Force Feedback Sustainer system

3.2.2 Signal Processing for Better Phase Coherency.

As hinted above, not all sensors sense the same property of a sound-making element. When feeding a string sensor's signal back into itself, one may find it beneficial to consider what exactly the sensor is measuring: a string's position, velocity, or acceleration? The implications of the sensing method on feedback actuation may not be initially obvious, but careful consideration and signal processing can increase system efficiency to use less power and increase headroom before detuning occurs. For Lorentz Force actuation, using a signal proportional to a string's own velocity appears to be most effective.

Position Signal: Optical sensors are a less common form of vibration sensing than coil or piezo pickups in the realm of musical instruments, but they have been explored commercially[7], academically [4, 17, 35], and by hobbyists [?] alike. This sensing method produces a voltage proportional to the displacement of a string from its resting, unperturbed position on one of its two vibrational axes.

Actuating a string with its own position signal can achieve an infinite sustain, but this is not a particularly efficient use of power to sustain resonance. Pushing a child on a swing set is a wonderfully intuitive analogy to a string sustainer, where the pusher adds external energy to the system to maintain the resonance of the swinging child. If one were to push the child with an increasingly greater force as it gets further from the resting center point (as in, using the child's position to dictate pushing force), the inefficiency immediately becomes apparent: while the child is on their upswing, the pusher starts out pushing gently, gradually pushing harder as the child moves further from the resting point of the swing. However, even once the child has reached the peak and begins to swing backwards, the pusher continues to attempt to push forward through their downswing, resisting the child's return. This half-cycle repeats in the other direction and

[7]https://www.light4sound.com and https://www.willcoxguitars.com/lightwave-optical-pickup-system/

resonant motion might be sustained, but a considerable amount of unnecessary work is being performed.

Velocity Signal: Instead consider the scenario where the swinging child is pushed with a force proportional to their traveling velocity: as they approach the peak of a swing cycle, slow down, and change directions, the pusher eases off and changes the direction of their push as well. The force from the pusher is now supporting the motion throughout the entirety of each resonant cycle, pushing the hardest when the child is moving fastest.

Much like the swing set example, it is more efficient to sustain a string's vibrations by only adding energy to the string while it is already in motion. By taking the first-order derivative of a position reading and feeding that back into the string, we observed that this could yield the same sustained volume at a fraction of the actuation power. However, we reiterate that sustain was absolutely possible without differentiation – this is not a fundamental requirement but rather a form of optimization (and an especially useful one if a system is experiencing detuning issues or power limitations). Solenoid coil sensors such as guitar pickups need no further processing to achieve low-power sustain because the sensed signal is already proportional to the appropriate velocity signal, explaining why this processing can typically be ignored in a feedback system that uses coils for both sustaining and actuating.

Acceleration Signal: Another common form of sensing used in musical instruments is a piezo-electric element. These sensors output a voltage proportional to the force exerted by the string if the string is sitting directly on the sensor (as is done in [4, 16]), which is proportional to the acceleration of the string. Presumably, this signal could be integrated to achieve a velocity signal.

3.2.3 Closed-loop Sensor and Magnet Placement.

In the case of closed-loop feedback actuation, sensor placement and magnet placement both play critical but less predictable roles. Similar to open-loop actuation, placing the magnet near the nut or bridge favors and emphasizes higher harmonics, and towards the center of the string tends to emphasize lower harmonics. The result of sensor placement is similar, with sensing towards the center being more fundamental-heavy than sensing near the nut or bridge. In practice, sensing towards the center of a string can prove impractical since this is where the displacement of a vibrating string is greatest. For example, an optical sensor with a limited working range may produce a distorted signal when placed more centrally. Overall, the harmonic result of a closed-loop sustain can vary drastically with sensor placement, magnet placement/polarity, and actuation signal polarity (e.g., inverting the magnet's pole can damp out the fundamental frequency and emphasize a higher harmonic instead, similar to an eBow's 'harmonic' mode). Although Co-location of the sensor and magnet should theoretically yield the most predictable and controlled version of infinite sustain (as explained and demonstrated by Ierymenko and Berdahl [6, 20]), practical experimentation with placement is effective for exploring timbre, and the nonlinearities introduced by non-collocated control, sensor distortions, and analog circuitry may yield sonically desirable feedback.

3.3 Dynamic Control via Amplitude Limitation

Amplitude limitation placed in the feedback loop can add a level of control and dynamics to the string sustain so that feedback is not simply *On* or *Off*. Note that this is different from simply controlling the gain of the feedback loop, but is instead an amplitude limiter – a special case of compressor – that prevents feedback from building over a threshold, where the threshold becomes the parameter that can be controlled dynamically.

This introduces an additional loop of feedback that provides the system awareness of a string's current vibrational amplitude as seen by the optical sensor via a volume detector. Consequently, the loop only adds energy to the system when the current amplitude measurement is below the threshold value to the volume comparator, and stops adding energy when has reached the threshold value. The result is the ability to control the amplitude of sustained vibrations on a string (Figure 6).

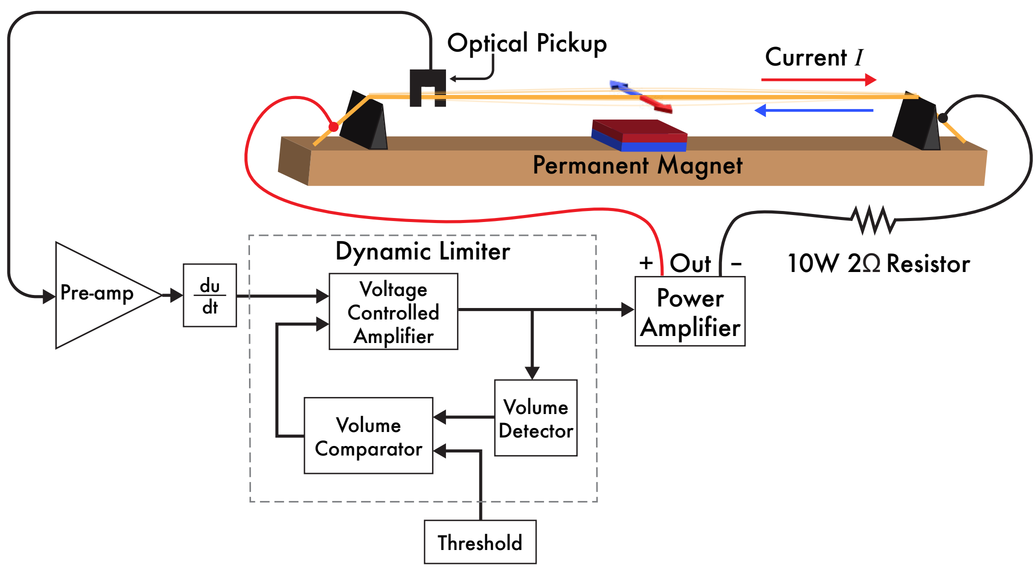

Figure 6: Lorentz Force string sustainer with differentiation and dynamically-controllable amplitude

4 Case Study: The Sparksichord

In the summer of 2023, University of Michigan School of Music Associate Professor Dr. Joseph Gascho reached out inquiring if the same concepts used in the Magnetic Resonator Piano [23] could be applied to a harpsichord. The initial goal of the Sparksichord was to use the existing keyboard interface to control the sustaining of the string corresponding to each string. Successful experiments on multiple different harpsichords strung in brass followed with several iterations of analog electronics development. Once ready to augment a full harpsichord, a 1970's Zuckermann 'Z-Box' Harpsichord already owned by the second author became the subject of our augmentation. Audiovisual documentation of our specific implementation can be found in the accompanying github repository[8], alongside our PCB design files, bill of materials, LTSpice circuit simulations, and more.

4.1 System Overview

The Sparksichord is a practical implementation of a 4-octave, 48-channel Lorentz Force sustainer system. Though only 48 of its 57 strings are actuated, all of its strings are brass opposed to a more traditional split of brass, iron, and steel. Its original keyboard is continuously sensed with optical sensors to control the volume of each string's actuation.

[8]https://github.com/aschmidt99/Sparksichord_NIME2025

A diagram of the signal flow of each string actuator channel is shown in Figure 7. In addition to being controlled by the harpsichord's own keyboard manual, it can alternatively be controlled with on-board potentiometers or control voltages from external sources such as modular synthesizers via 3.5mm mono jacks. The strings can either be in *sustain mode*, where they are fed a signal from their respective optical pickups, or *audio actuation mode*, where an arbitrary audio signal can be fed into the string. Each channel can be fed an independent signal via 3.5mm mono jacks, or a global stereo signal can be sent to all 48 channels of the board, where each channel can be switched to the 1st ('left') or 2nd ('right') audio channel via a 3.5mm stereo jack. While a key press for a given channel activates the sustainer feedback in *sustain mode*, the same key press control allows an external arbitrary audio signal to excite its respective string when in *audio actuation mode*. The mode is can be changed with the flip of the 'mode' switch, which is an independent control for each string.

4.2 Optical String Sensing

An array of ITR20403 optical sensors is used to individually sense the vibrations of each string, and the sensing circuit for each channel is similar to the schematic described by Dave Corsie (https://www.davecorsie.com/optical-pickup-blog). The sensors are mounted on an aluminum rail that is fastened to the harpsichord's original jack rail (Figure 9).

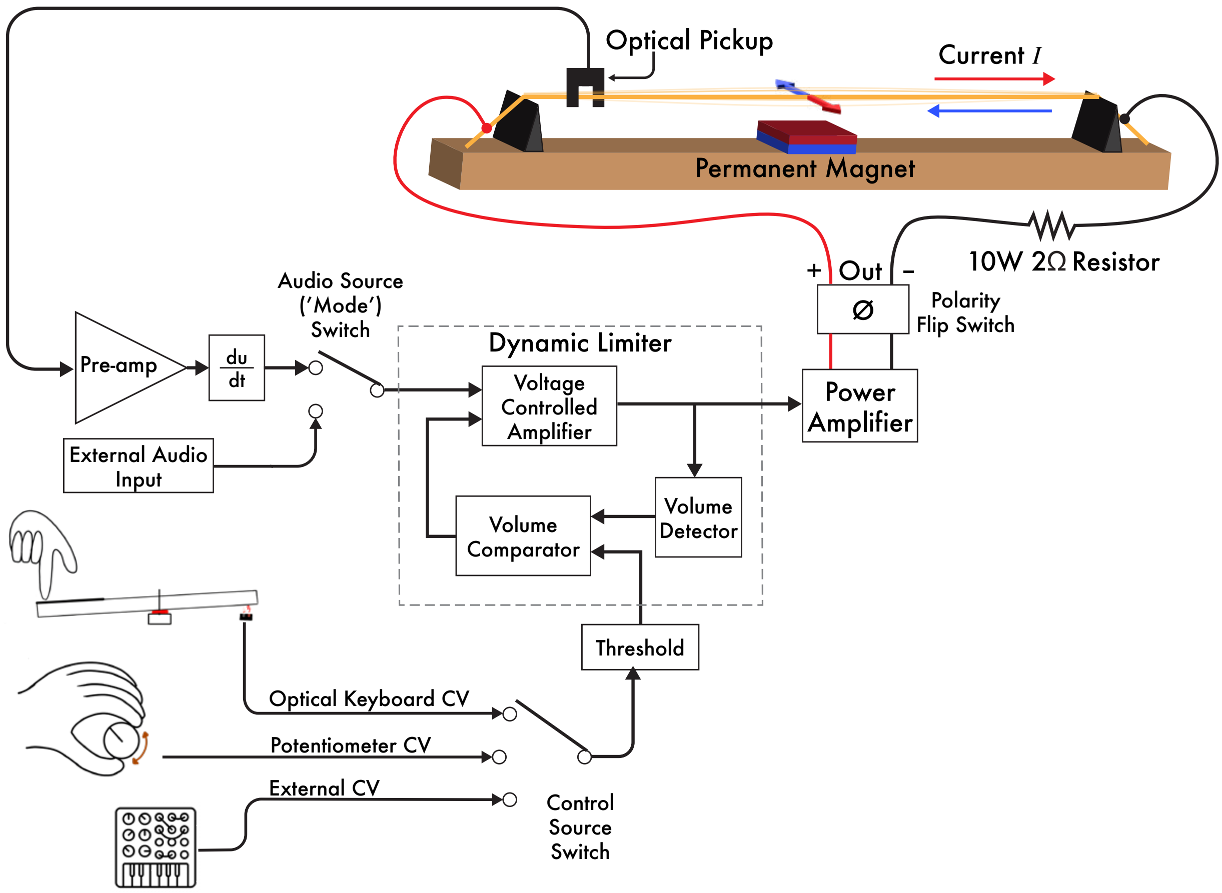

Figure 7: Full system diagram for one string of the Sparksichord

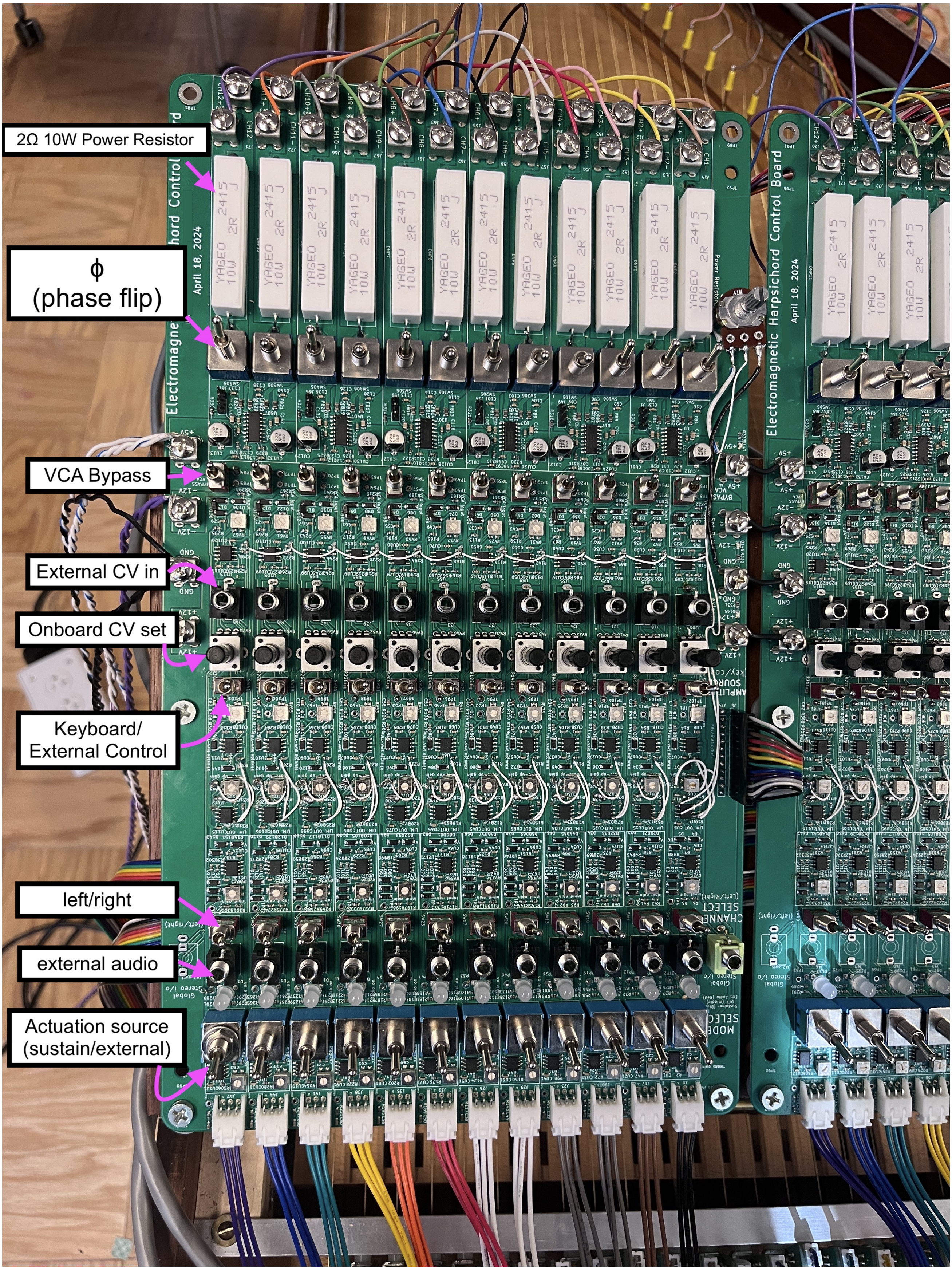

Figure 8: 12-channel Sustainer Board and its controls

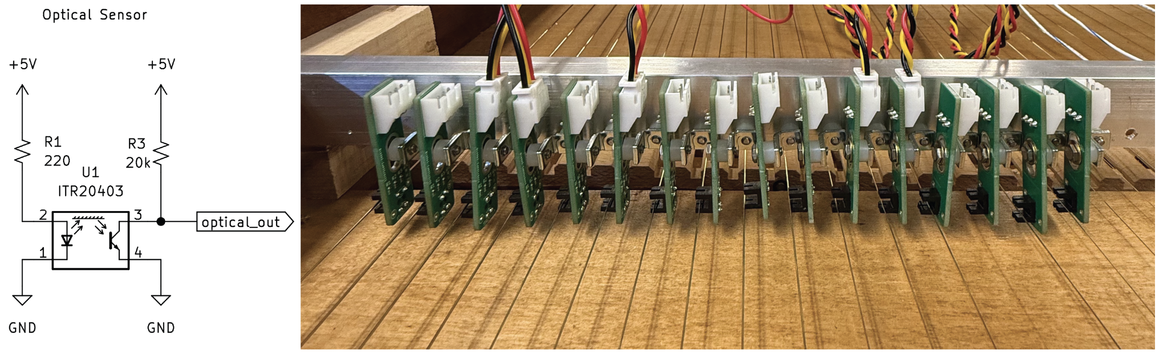

Figure 9: Optical String Sensor Schematic & the array mounted above strings

4.3 String Signal Processing, Power Amplifier, & Power Resistors

Figure 8 depicts one of the four 12-channel circuit boards. Each channel of the board contains an optical gain, differentiation, and limiter circuit. Various jacks, switches, and potentiometers allow a player/composer flexibility in how each string behaves.

The op-amp differentiator circuit in Figure 10 is used for obtaining our string velocity signal, where R18 and C3 are essential for differentiation and R15 and C5 are added for circuit stability. The voltage-controlled limiter circuit was based on a diode compression circuit designed by Moritz Klein[9]. Thorough documentation detailing the details of its implementation can be found online[10], and our implementation is provided in Appendix A.

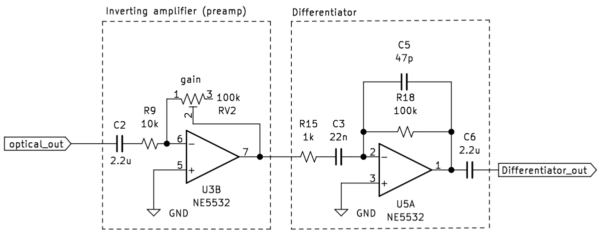

Figure 10: An op-amp preamplifier and differentiator

To actuate each string, a PAM8406 Speaker Amplifier IC was used, paired with a 2Ω 10W power resistor in series with each string. Many speaker-driving power amplifiers are designed to drive a load of 4Ω-8Ω as a typical speaker's voice coil is expected to be. The PAM8406 IC is one such amplifier, and it is designed to shut itself off for its own protection when it detects a load <2Ω. When the (+) and (-) terminals of the chip's speaker outputs are connected to each end of a string, an especially conductive instrument string may appear as a short circuit and put the chip into shutdown mode. A workaround was identified by placing a power resistor in series with the conductive string to create a total resistance >2Ω. Depending on string's resistance (which is a function of length, diameter, and material conductivity), resistors on the order of 0.5Ω-2.0Ω are all reasonable so long as the total resistance of the string + power resistor is >2Ω.

4.4 Adjustable Magnet Rail

It was identified early in the augmentation that magnet position was important and being able to adjust the position of each magnet would be desirable. Therefore, a rail that contains 24 neodymium magnets in 24 parallel slots was designed and laser cut out of layers of clear acrylic and plywood. Each magnet is sufficiently close enough to 2 brass strings each to allow actuation and sustaining to occur (Figure 11). The slots allow for the magnet positions to be adjusted by sliding a magnet or piece of steel closely over a given magnet (Figure 12). Though this arrangement does not maximize the Magnetic Flux **B** through each string, it increases the stability of the magnets so they are not trying to pushing one another away, and this arrangement should ensure long-term stability of their magnetic strength.

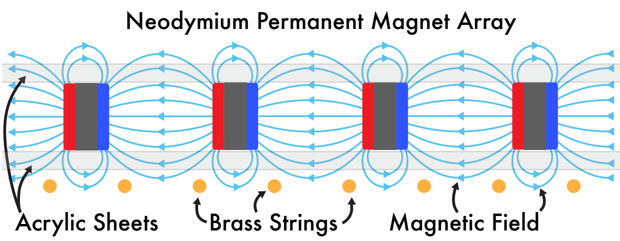

Figure 11: Side view of magnets and strings (where strings are going into the page)

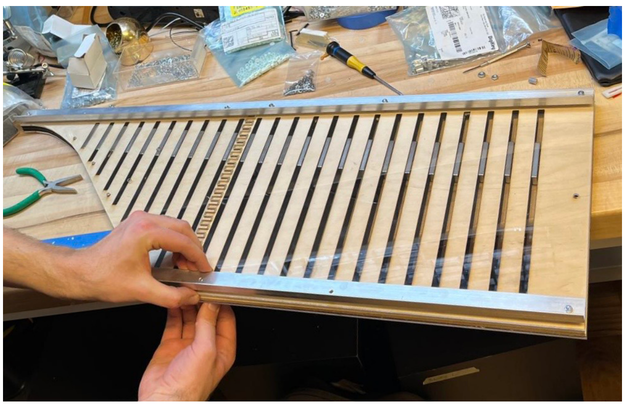

Figure 12: Laser-cut Magnet Rail

[9]https://www.youtube.com/@MoritzKlein0
[10]Video Guide and Written Guide

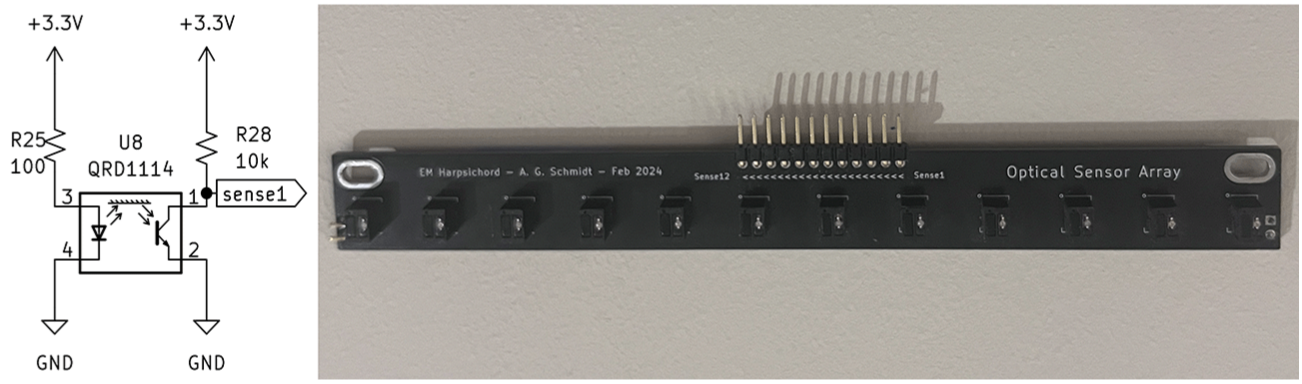

Figure 13: Optical Key Sensor Schematic & 12-channel optical keyboard sensor

4.5 Optical Key sensing

An array of 48 QRD1114 optical reflectance sensors were installed beneath the keyboard manual, resting at the end of the key levers. The sensors work using the same principle as the optical pickup sensors, though these are arranged to measure the infrared reflectance off of a nearby object rather than an object obstructing its view. As the keys are unpressed, the back of the lever rests very close to the optical sensor, maximizing reflectance and activating the optical sensor so that its output voltage is nearly $0V$. As a key is depressed, the back of the lever is further away from the sensor, reflecting less infrared light back to the sensor and raising the output voltage of the sensor. The compression/limiter circuitry that enables dynamic range in the playing of the Sparksichord anticipates a control voltage range of approximately 0 Volts to 3.3 Volts, where 0V allows no actuation to occur and 3.3V allows for full actuation. To obtain the desired voltage swing from the QRD1114 sensors as a key is pressed, the back of each key lever was first painted black, and then a small dot was carved out of the black paint approximately where the sensor rests under the key. The circuit for a single channel can be seen in Figure 13. This arrangement and sensing method is nearly identical to the keyboard scanner used in the MRP [25] which consists of an array of QRE1113 Optical Reflectance sensors over the keys of any piano. The pictured system is permanently installed rather than removable, and is designed specifically for the spacing of these keys since harpsichord key widths are not standardized. The sensor array can be seen in Figure 14.

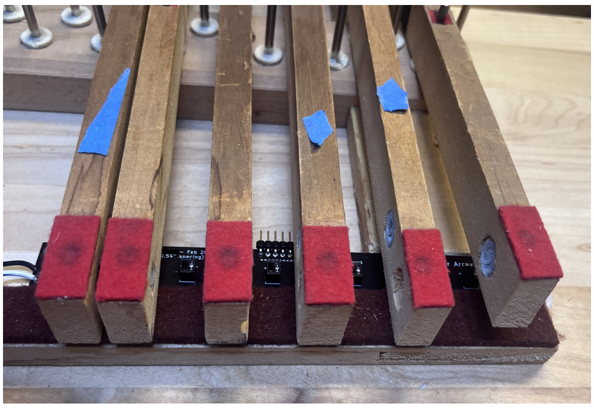

Figure 14: View of optical array from behind the manual – the rightmost key is depressed from the player's position

5 Discussion

5.1 Comparison to other systems

It is difficult to directly compare styles of actuation as they have different requirements and implications, although we attempt to describe some pros, cons, and considerations in Table 1.

The Sparksichord closely resembles other electromagnetically-actuated instruments such as the MRP; both are keyboard instruments with an array of strings use electromagnetic actuation. However, the design challenges and choices made to create the Sparksichord and MRP are deeply entangled with their inherent properties prior to augmentation. For example, the iron frame and metal bridges of a piano means its steel strings are electrically connected, and consequently Lorentz Force actuation of a piano would require significant mechanical overhaul, design, and reconfiguration to implement. Conversely, the wooden nut and bridge of the harpsichord means every string is already electrically isolated and more practical for Lorentz Force actuation. Furthermore, the brass strings of the harpsichord are considerably more electrically conductive than the steel of pianos and therefore offer greater tuning stability at the electrical current values needed for actuation and sustain. Although it is not uncommon to see all-brass harpsichord stringing schedules – particularly in Italian harpsichords – we had restrung the Zuckermann harpsichord in all brass. However, after experiencing a few of the higher octave strings breaking when bringing them up to pitch and a brief consultation with Zuckermann Harpsichords, we decided to tune the whole instrument a major third down.

5.2 Analog Circuits, Materials, Feedback, and Chaotic Behavior

5.2.1 *Analog Circuitry.*

This project was implemented using exclusively analog circuitry primarily due to the first author's background and comfort with analog design, and secondarily for the potential benefits of analog design for feedback actuation. To have the best chance at phase-coherence between the sensing method and actuation method, there would ideally be no time delay between them. Digital systems, however, introduce a time delay that will shift the phase response with respect to frequency due to their inherent processing time. Ultra-low latency processing optimized for audio (as offered by some microcontrollers or purpose-built FPGAs) may be used to mitigate this latency and introduce the opportunity for the flexibility and control of a digital system. Professional-grade compressors and limiters are designed to minimize undesirable

EM Coil Actuation Style 1: driving a ferrous object	EM Coil Actuation Style 2: driving a permanent magnet	EM Coil Actuation Style 3: Speaker coil or Transducer Coil	Lorentz Force Actuation
• Must be ferromagnetic material (iron or steel). • High power requirements for open-loop actuation • Medium for closed-loop sustain • Higher frequencies may be more difficult to induce	• Can be any material • Fixing magnets to a resonant object may alter its expected resonance • Actuation force scales with magnet strength • Higher frequencies may be more difficult to induce	• Can be any material • Less predictable transfer function between sensor and actuator • Higher frequencies may be more difficult to induce	• Must be conductive (highly conductive to avoid detuning) • Requires electrically-isolated strings • Actuation force is lower than other methods for the same current and magnetic field • May require a non-coil sensing method (optical, piezo, etc) • Higher frequencies are easier to induce

Table 1: Comparison of EM Coil Actuation Styles and Lorentz Force Actuation

audio distortion, and parameters such as a limiter or compressor's attack, release, and ratio are dialed in to mitigate distortions and non-linearities. However, the limiter circuit implemented is relatively simple, and we opted to use a fast attack and 100% ratio. Simulations of our diode-based compression circuit with these settings reveal that the feedback is subject to harmonic distortion, but when implemented in a real setting it accomplished the goal of dynamic control. The choice to remain entirely in the analog domain afforded a cheap and fast implementation compared to attempting to work with 48 channels of digital audio, but this limited our ability to prototype different feedback schemes.

5.2.2 *Material-Oriented Interaction and Design.*

Discussion surrounding material-oriented interaction [27] has become commonplace in NIME, and this work is no exception. Many musicians and practitioners are already intimately familiar – perhaps explicitly or implicitly – with the properties of an non-actuated string; the relationship between its length, weight, tension, etc. to its expected timbral quality and harmonic response when plucked, struck, or bowed. However, the introduction of electromagnetic feedback suddenly reveals the string's otherwise less-observed properties, such as conductivity or magnetic permeability, or unnaturally exaggerated harmonic modes. Due to the nature of using permanent magnets rather than wired electromagnetic coils, Lorentz Force actuation invites musicians to manually handle the magnets, bringing them near strings to initiate actuation in the same touchless and quasi-magical manner that has promoted continued fascination with the Theremin. Offering the magnet to different points along the length of a string, adjusting proximity, or flipping the orientation of the magnet offer especially interesting vantage points to dynamically modulate the system's behavior. Depending on the actuation current, frequency, and magnet size, one may even feel the actuation signals noticeably vibrate the magnet in their grasp[11]. We also discovered an intriguing mode of interaction while fine-tuning optical sensor placement, where shifting the optical sensors slightly such that they enter the nonlinear extremes of their operational range and encourage the feedback to settle into higher harmonics of the string, or in some cases creating a rich, droning timbre that periodically swirls between harmonics on the order of seconds. The response of the feedback can at times be slow, with graceful swells and decays within the harmonic profile. At other times, changes can be immediate and dramatic, responding to sub-millimeter changes in sensor placement and drawing parallels to the practice of no-input mixing (NIM) [28–30].

5.2.3 *Leaning away from control, inching towards chaos.*

It seems many earlier feedback instruments/devices such as the Magnetic Resonator Piano [23] and the Moog Guitar [20] share a common desire to hyper-control feedback by parameterizing controls. In recent years, however, there has been an influx of vibrotactile feedback instruments and practitioners that embrace chaotic, unpredictable behavior, many of whom cite this unpredictability as precisely what makes it so exciting and engaging [28, 29].

> *Playing with self-resonating feedback instruments demands that I pay close attention. The most satisfying feedback music seems to be at the thresholds and breaking points, and these are rarely stable. And this is a good thing, because stability (or equilibrium) actually means death, where uncertainty, chaos and contingent connections are the realm of the living.*
> – Paul Stapleton, in [15]

For many of these practitioners, improvising is particularly fruitful and perhaps the highlight of their systems [30], and similar sentiments are shared by those engaging with complex feedback in musical instruments [11, 14, 26, 38, 39]. Lorentz Force sustain offers a new vantage point for exploring chaotic feedback, and informal experiments with Lorentz Force actuation and optical sensing patched into the feedback path of a no-input mixing has been promising.

6 Conclusion

This paper has presented the theory behind Lorentz Force actuation/sustain and has offered practical considerations for implementation within a musical context. After outlining the fundamental ingredients needed to build a sustainer or feedback instrument of this style, we shared technical details of our multichannel sustainer harpsichord. We hope this document serves as a reference, empowering practitioners with a toolkit for designing new musical augmentations and inventions surrounding this style of string actuation, and we leave readers with reflections on how Lorentz Force actuation has the potential to lead to new paradigms of actuated instrument design.

[11]We feel obliged to remind readers to practice safety when handling permanent magnets, as we have personally experienced the occasional finger pinching (not to mention the numerous frights as unattended, forgotten, or misplaced magnets enthusiastically and explosively embrace one another and, in some cases, crack, shatter, or spark

7 Acknowledgments

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8 Ethical Standards

This stage of the research is focused on technical development and testing by the authors, so institutional ethics review for human subjects research has not yet been necessary. Electrical safety should be considered with any actuated instrument, though the risks in this setup are low given low power supply voltages and internal short-circuit protection in the amplifiers. Any future extensions of this work to historical harpsichords would need to consider issues of conservation and of the inevitable tensions between historical and experimental performance practices.

References

[1] Lior Arbel, Yoav Y. Schechner, and Noam Amir. 2019. The Symbaline — An Active Wine Glass Instrument with a Liquid Sloshing Vibrato Mechanism. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Porto Alegre, Brazil, 9–14. https://doi.org/10.5281/zenodo.3672848

[2] Eugene A Avery. 1933. *The Electrical Resistance of Metals in Their Hard and Soft States*. B.S. Thesis. Montana School of Mines.

[3] Edgar Berdahl. 2009. *Applications of Feedback Control to Musical Instrument Design*. Ph. D. Dissertation. Stanford University, Stanford, California, USA.

[4] Edgar Berdahl and Julius O Smith III. 2006. Active Damping of a Vibrating String.. In *International Symposium on Active Noise and Vibration Control*. Adelaide, Australia.

[5] Edgar Berdahl, Guenter Niemeyer, and Julius O. Smith. 2008. Active Control of a Vibrating String. *The Journal of the Acoustical Society of America* 123 (May 2008), 3666. Issue 5. https://doi.org/10.1121/1.2934997

[6] Edgar Berdahl, Julius O. Smith, and Günter Niemeyer. 2012. Feedback Control of Acoustic Musical Instruments: Collocated Control Using Physical Analogs. *The Journal of the Acoustical Society of America* 131, 1 (Jan. 2012), 963–973. https://doi.org/10.1121/1.3651091

[7] Per Bloland, Richard Causton, and Henri Boutin. 2025. Artistic Research Residency Seminar | Per Bloland, Richard Causton & Henri Boutin - YouTube. https://www.youtube.com/watch?v=1t3cSMtNFj0

[8] Henri Boutin. 2011. *Méthodes de contrôle actif d’instruments de musique. Cas de la lame de xylophone et du violon*. Ph. D. Dissertation. https://doi.org/10.13140/RG.2.1.4620.4966

[9] Henri Boutin, Charles Besnainou, and Jean-Dominique Polack. 2015. Modifying the Resonances of a Xylophone Bar Using Active Control. *Acta Acustica united with Acustica* 101 (April 2015). https://doi.org/10.3813/AAA.918836

[10] N. Cameron Britt, Jeff Snyder, and Andrew McPherson. 2012. The EMvibe: An Electromagnetically Actuated Vibraphone. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. The University of Michigan, Ann Arbor, MI, USA.

[11] Tom Davis. 2017. The Feral Cello: A Philosophically Informed Approach To An Actuated Instrument. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Zenodo, Aalborg University, Copenhagen, Denmark. https://doi.org/10.5281/ZENODO.1176250

[12] E. Paul DeGarmo. 2003. *Materials and Processes in Manufacturing. 2003.* (9th ed., update ed ed.). Wiley.

[13] Richard Eisenmann. US Patent No. 496402A, 1893. Elektrophonisches Klavier.

[14] Alice Eldridge and Chris Kiefer. 2017. Self-Resonating Feedback Cello: Interfacing Gestural And Generative Processes In Improvised Performance. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Zenodo, Copenhagen, Denmark. https://doi.org/10.5281/ZENODO.1176157

[15] Alice Eldridge, Chris Kiefer, Dan Overholt, and Halldór Úlfarsson. [n. d.]. Self-Resonating Vibrotactile Feedback Instruments ||: Making, Playing, Conceptualising :||. In *Proceedings of the International Conference on New Interfaces for Musical Expression*.

[16] Adrian Freed and Osman Isvan. 2000. Musical Applications of New, Multi-axis Guitar String Sensors.

[17] Roger Hanson, James Anderson, and H. Kent Macomber. 1994. Measurements Of Nonlinear Effects In A Driven Vibrating Wire. *Journal of the Acoustical Society of America* 96, 3 (Jan. 1994), 1549–1556. https://doi.org/10.1121/1.410233

[18] Jiffer Harriman. 2015. Feedback Lap Steel : Exploring Tactile Transducers as String Actuators. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Louisiana State University, Baton Rouge, LA, USA.

[19] Gregory S. Heet. US Patent No. 4075921A 1978. String Instrument Vibration Initiator and Sustainer.

[20] Paul F. Ierymenko. Patent EP1218716B1, 1999. Unitary Transducer Control System.

[21] Paul F. Ierymenko. US Patent No. 20100275761A1, 2010. Player Technique Control System for a Stringed Instrument and Method of Playing the Instrument.

[22] Alvin Lucier. 1980. Music On A Long Thin Wire. Vinyl. Lovely Music, Ltd., VR 1011/12.

[23] Andrew McPherson. 2010. The Magnetic Resonator Piano: Electronic Augmentation of an Acoustic Grand Piano. *Journal of New Music Research* 39, 3 (Sept. 2010), 189–202. https://doi.org/10.1080/09298211003695587

[24] Andrew McPherson. 2012. Techniques and Circuits for Electromagnetic Instrument Actuation. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. The University of Michigan, Ann Arbor, MI, USA.

[25] Andrew P McPherson. May 27 – 30, 2013. Portable Measurement and Mapping of Continuous Piano Gesture. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Daejeon, Korea.

[26] Adam Pultz Melbye. 2021. Resistance, Mastery, Agency: Improvising with the Feedback-Actuated Augmented Bass. *Organised Sound* 26, 1 (April 2021), 19–30. https://doi.org/10.1017/S1355771821000029

[27] Tom Mudd. 2019. Material-Oriented Musical Interactions. In *New Directions in Music and Human-Computer Interaction*. Springer, 123–133. https://doi.org/10.1007/978-3-319-92069-6_8

[28] Tom Mudd. 2023. Playing with Feedback: Unpredictability, Immediacy, and Entangled Agency in the No-input Mixing Desk. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI ’23)*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3544548.3580662

[29] Tom Mudd and Akira Brown. 2023. Musical Pathways through the No-Input Mixer. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Mexico City, Mexico.

[30] Tom Mudd, Simon Holland, and Paul Mulholland. 2019. The Role of Nonlinear Dynamics in Musicians’ Interactions with Digital and Acoustic Musical Instruments. *Computer Music Journal* 43, 4 (Dec. 2019), 25–40. https://doi.org/10.1162/comj_a_00535

[31] Dan Overholt. 2011. The Overtone Fiddle: An Actuated Acoustic Instrument. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. https://doi.org/10.5281/ZENODO.1178127

[32] Dan Overholt, Edgar Berdahl, and Robert Hamilton. 2011. Advancements in Actuated Musical Instruments. *Organised Sound* 16, 2 (Aug. 2011), 154–165. https://doi.org/10.1017/S1355771811000100

[33] Laurel Pardue, Kurijn Buys, Dan Overholt, Andrew P. McPherson, and Michael Edinger. 2019. Separating Sound from Source: Sonic Transformation of the Violin through Electrodynamic Pickups and Acoustic Actuation. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Porto Alegre, Brazil, 278–283. https://doi.org/10.5281/zenodo.3672958

[34] Martin Piñeyro. 2012. Electric Slide Organistrum. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Zenodo, The University of Michigan, Ann Arbor, MI, USA. https://doi.org/10.5281/ZENODO.1180571

[35] Adam Schmidt and Michael Gurevich. 2024. The Lorentz Lap Brass: Method for Frugal Integrated Sonic/Haptic Interaction. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Utrecht, NL.

[36] Greg Shear and Matthew Wright. 2012. Further Developments in the Electromagnetically Sustained Rhodes Piano. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. The University of Michigan, Ann Arbor, MI, USA.

[37] Halldór Úlfarsson. 2018. The Halldorophone: The Ongoing Innovation of a Cello-like Drone Instrument. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Blacksburg, VA, USA.

[38] Halldór Úlfarsson and Adam Pultz Melbye. 2020. Sculpting the Behaviour of the Feedback-Actuated Augmented Bass. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Birmingham, United Kingdom.

[39] Federico Visi. 2024. The Sophtar: A Networkable Feedback String Instrument with Embedded Machine Learning. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Utrecht, Netherlands, 142–148. https://doi.org/10.5281/zenodo.13904810

[40] Marc Wijnand, Brigitte d’Andréa-Novel, Thomas Hélie, and Roze David. 2024. Experimental Implementation of a Finite-Time Controller for the Axisymmetric Vibration Modes of a Tom-Tom Drum - Archive Ouverte HAL. (2024).

A Schematics

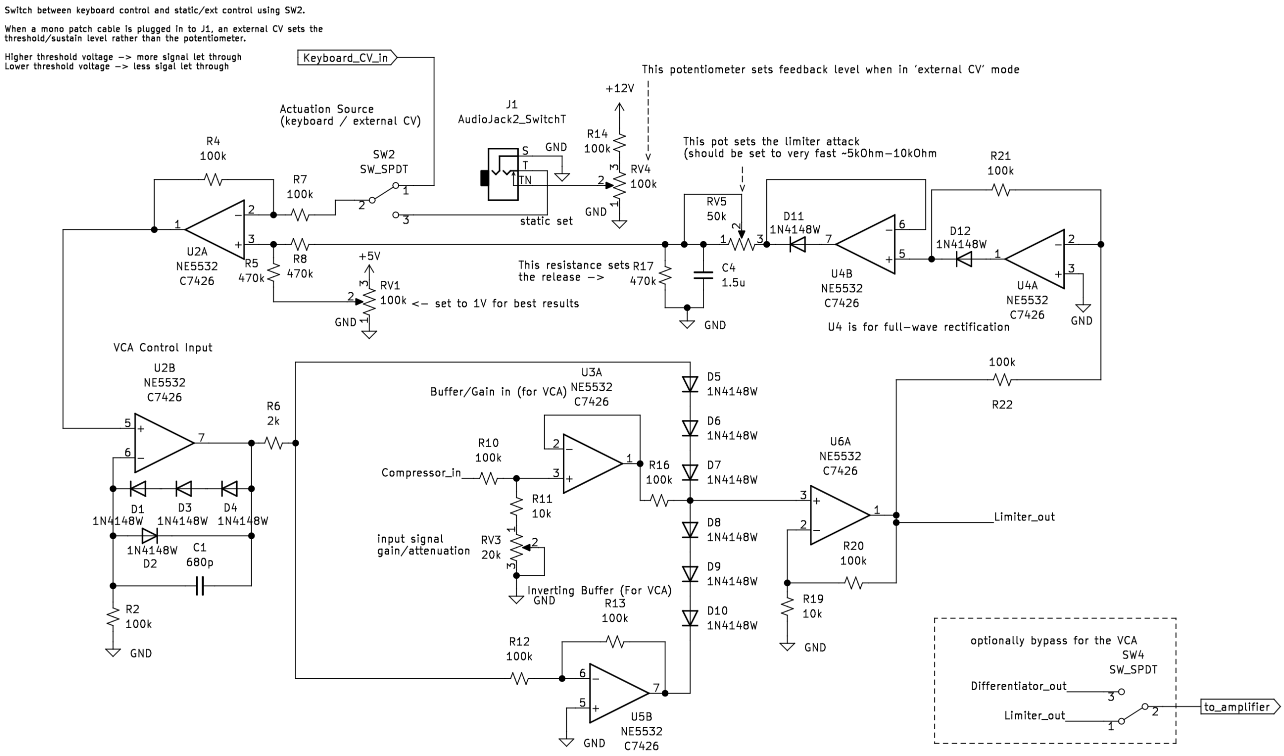

Figure 15: Limiter Circuit

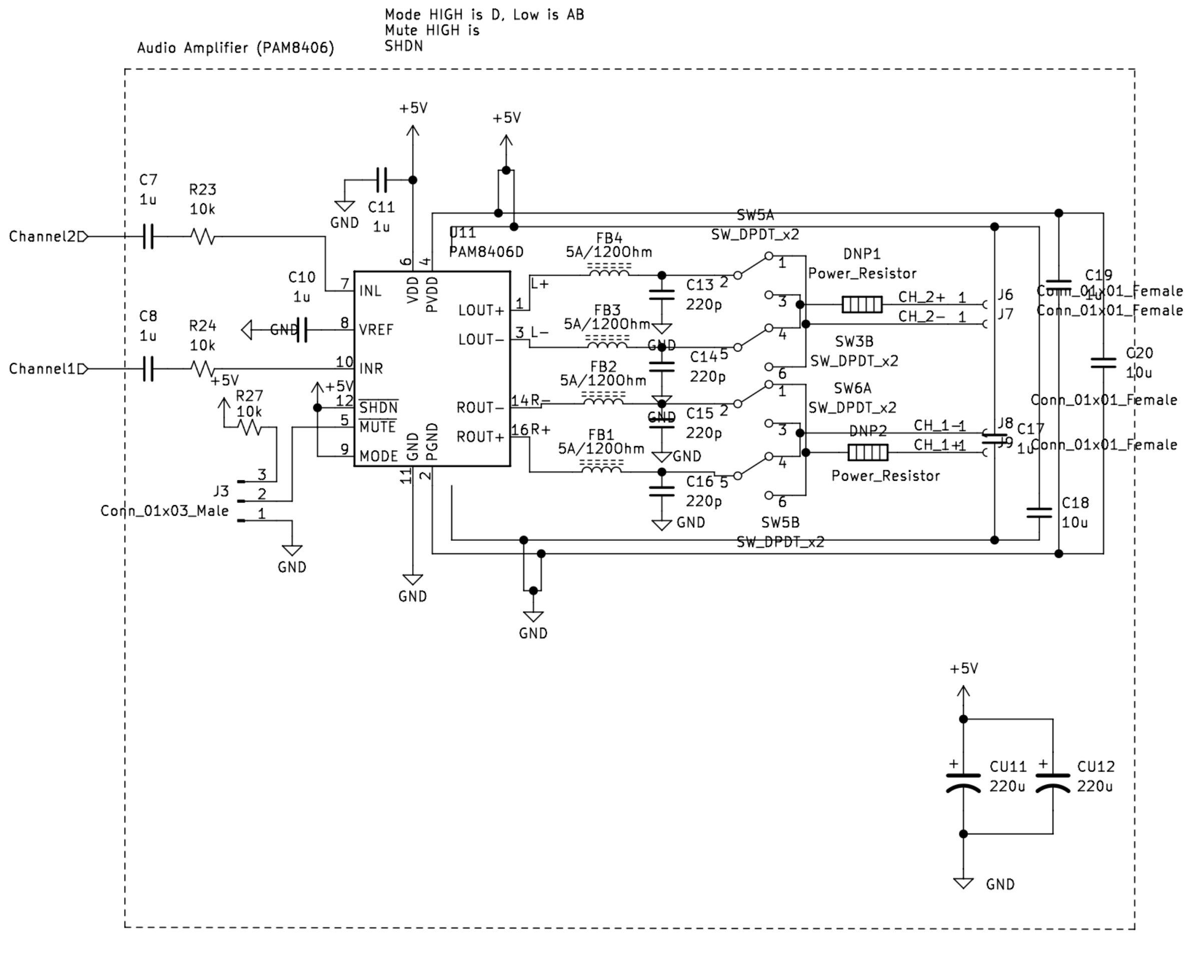

Figure 16: Circuit Configuration for PAM8406