Sustained Interests: Active Collocated String Control with Lorentz Time Division Multiplexing

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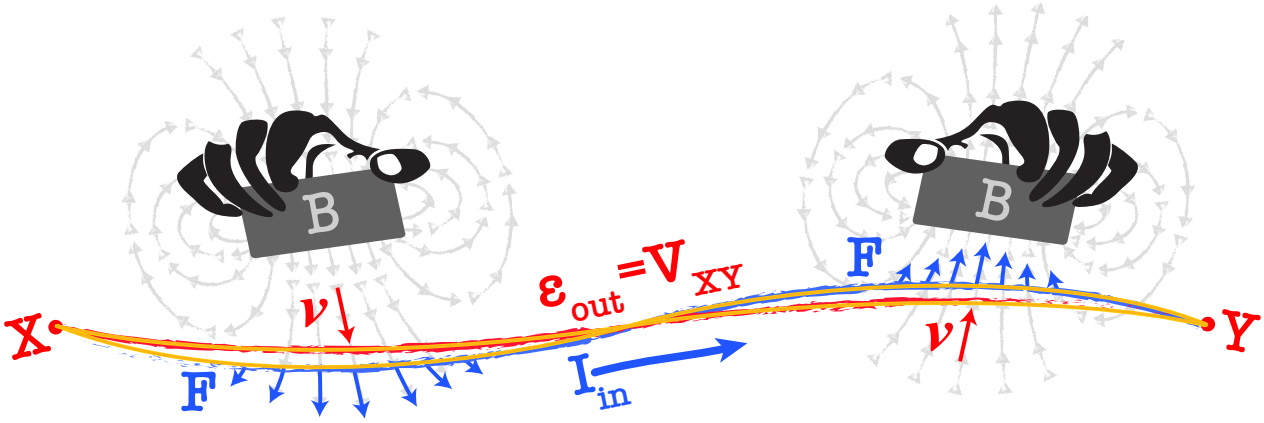


Figure 1: Using magnets and an electrically conductive musical instrument string as a sensor and actuator simultaneously. Applying current I induces force F while velocity v induces voltage ε.

Abstract

This work introduces Lorentz Time Division Multiplexing (LTDM), a technology that actively sustains vibrations on conductive instrument strings by exploiting the inherent bilateral nature of electromagnetism. Though many feedback instruments depend on using separate, external sensors and actuators to monitor and induce vibrations in a string, our LTDM controller initiates and sustains vibrations by running electric current through the string itself. By connecting custom circuitry to a conductive string via two electrical leads, strings vibrate and self-sustain when a permanent magnet is held or fixed in close proximity without the need for external sensors or actuators. Unlike most feedback instrument methods to date, the inherently collocated nature of LTDM affords coherent control without specialized calibration and can be easily deployed from instrument to instrument with minimally invasive augmentation. A pair of contrasting case studies demonstrate some of these new sonic qualities and playing techniques we have observed thus far from the same metal strings musicians have used for centuries.

Keywords

Electromagnetic actuation, sustain, augmented instruments, Lorentz Force, EMF sensing

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1 Introduction

We have fused an electronic control method called time-division multiplexing (TDM) with a recent research thread of a particular string actuation technique called Lorentz force actuation [41, 42], creating what we call Lorentz Time-Division-Multiplexing (LTDM). This form of feedback actuation allows for a unique exchange of energy between acoustic, mechanical, electrical, and digital domains, permitting behavior not typically exhibited by Digital Musical Instruments (DMIs) or existing feedback-actuated instruments. Building on decades of sustained interest in electromagnetic feedback instruments within academic, experimental music, maker/DIY communities, and recent commercial uptake, this paper explores the affordances and constraints of LTDM and compares it to other electromagnetic actuation methods.

Rather than striking, plucking, or bowing a string to create sound from a musical instrument, LTDM allows us to inject energy into a string electromagnetically without necessarily physically touching the string. This method allows us to indefinitely sustain vibrations on strings via our hardware controller with just a pair of electrical leads and a permanent magnet and without interfering with traditional excitation methods. Our design has a similar motivation to many prior works in this space; to expand the sonic palette available to a musical instrument player. However, as we will expand on in Sections 2.5 and 3.3, our implementation bypasses some of the design bottlenecks of prior feedback actuation methods and allows us to ignore most of the calibration, setup, and tuning required of other systems and focus instead on the sonic exploration, embodiments, and implications of this technology. Our research begins to address some of the many challenges identified by the Feedback Musicianship Network, including the need for improved design and scientific

understanding of actuation technologies, the unification and formalization of conceptualization of and language surrounding these instruments, and the development, documentation, and support of feedback-based artistic practices [19, 20, 36].

After first discussing some background and prior art, this paper describes the theory behind LTDM and follows up with a practical technical implementation. LTDM is then exemplified by a pair of contrasting instruments - one augmented and one invented – and the behaviors of each system are compared. Finally, the affordances and limitations of LTDM on both technical and musical levels are discussed.

2 Related Work

2.1 Embodied Sound

Over the past decades, increased access to and education surrounding digital sound synthesis methods have seen sound-making strategies increasingly migrate from the acoustic domain to the digital domain. However, the pendulum may be swinging back in the other direction as musicians rediscover the richness and physicality of acoustic sound production; acoustic and certain classic electromechanical instruments such as the Fender Rhodes and Hammond Organ are prized for their responsive materiality and physical presence [13, 25, 30], and new commercial electromechanical[1] and feedback-actuated[2] instruments continue to emerge, hinting at a renaissance of embodied sound production.

2.2 Electromagnetically-Actuated Instruments

Electromagnetic actuation is a popular method for designing actuated instruments. Many use magnetic coils in the form of solenoid electromagnets, vibration transducers, or cone loudspeakers to electromagnetically induce physical vibrations in a resonating body [1, 8, 11, 21, 26, 28, 35, 39, 43, 45], though other methods of actuation are also possible (e.g., piezo-element actuation [10, 17]. Lorentz force actuation is an alternative electromagnetic actuation method to coil actuation, whereby force is applied to a conductive wire by running an electric current through it while exposed to an external magnetic field [24, 41, 42] and will be expanded on in Section 3.1. Perhaps the most famous artistic use of this technique is Alvin Lucier's *Music on a Long Thin Wire*, where Lucier used a power amplifier intended to drive speakers to instead actuate a long conductive wire [24].

2.3 Feedback Instruments & 'Infinite Sustain'

Many previous instrument actuation systems are *open-loop*, meaning their magnets, strings, or tonebars are driven by actuators fed with synthesized or pre-recorded signals [1, 11, 24, 26]. A subcategory of the actuated instrument is the feedback-actuated instrument, whereby a sensor actively monitors the vibrations of the instrument. The sensed signal is then used directly or processed to drive the actuator to actively alter vibration in the system. In control theory, this is called *closed-loop* feedback. A classic style of feedback-actuated instrument uses positive closed-loop feedback to resonate its sound-producing elements indefinitely, and commonly referred to as *infinite sustain*.

To create an infinitely sustaining feedback system, the fundamental requirements are:

(1) a resonant element (a tensioned string, membrane, air cavity, bar, etc.)
(2) a method of sensing the vibrations of the resonant element
(3) a method of inducing vibrations into (i.e. actuating) the vibrating element
(4) a loop gain between the sensor and actuator great enough to support self-sustaining oscillation at one or more frequencies

Feedback is enabled in instruments like the Halldorophone and Feedback-Actuated Augmented Bass (FAAB) by sensing vibrations of one or more elements of the instrument and physically driving a different element of the instrument [28, 44, 47]. For example, the Halldorophone has electric guitar-style pickups that sense individual string vibrations, but is actuated with a single speaker fixed to its body. Recent developments in feedback-actuated instruments are sculpted by advancements in digital fabrication, electronics prototyping, real-time computing, and the crystallization of feedback instrument aesthetics [19, 31, 36].

2.4 Hybrid Digital-Acousto-Electro-Mechanical Instruments

Ongoing research explores how signal processing can enable digitally-simulated components in analog circuits [5, 6, 33, 46] or actively influence the physical realm through real-time transformation of the acoustic properties of a room [29] or vibrating element [3, 7, 10]. These controllers still use tightly-controlled feedback between sensors and actuators to alter the mechanical or electrical properties of a resonant subject (e.g., the air in a room, a vibrating bar or string, or an oscillating inductor-capacitor circuit), but typically extend beyond the relatively straightforward case of 'infinite sustain', instead offering control over the damping, decay time, or resonant frequencies of their subject(s). These projects allow energy to be exchanged bidirectionally between electrical, mechanical, and acoustic domains, breaking down the typically unidirectional barrier between physical and digital systems [16]. This paper aims to investigate how novel instrument behavior might emerge from similar bilateral energy flow.

2.5 Collocated Control

Most existing feedback instruments have a separate sensor and actuator to achieve feedback. However, for improved stability and simplified implementation of closed-loop feedback actuation, the sensor and actuator should be physically located as close together as possible. This collocation minimizes mechanical propagation delay between them, reducing or eliminating the need to consider the transfer function between the sensing method and the actuating method [4, 22]. Correction methods can be used, but this requires precise calibration and setup, and deviation between calibration and implementation can cause system instability [2, 3, 9, 10].

A transducer used as both a sensor and actuator simultaneously can be referred to as a *sensoriactuator* [14]. To achieve collocated control, the sensing and actuating mechanisms must be isolated to prevent unwanted electrical crosstalk between the sensing and actuation signals. Our recent work describes how this can be achieved in a few different ways [15], such as an adaptive controller that models and subtracts the effect of the applied actuation signal to calculate a mechanically induced signal [14] or a controller that rapidly switches the transducer between sensor and actuator roles - also known as time-division multiplexing [22].

[1] https://gamechangeraudio.com/motor-synth-mkii/; https://circleinstruments.com; https://murobox.com/
[2] https://korg.berlin/products/phase8; https://www.physical-synthesis.com

3 Principles of Operation

This section serves as a high level explanation of the principle of operation behind Lorentz force actuation, the reciprocal case of EMF sensing, and time-division multiplexing (TDM). TDM bridges these actuation and sensing methods to become LTDM, creating a collocated sensoriactuator from a conductive string and permanent magnet(s).

3.1 Actuation: Lorentz Force

Lorentz force describes the magnetic force felt by a current-carrying wire exposed to a magnetic field and suggests how a conductive string can be used as an electromechanical/electroacoustic transducer. To generate a localized force vector on a conductive wire, all that is required is a method to apply a current through the string and an external magnetic field (Equation 2 and Figure 2).

$$\mathbf{F} = I \int d\mathbf{l} \times \mathbf{B} \tag{1}$$

When we assume a uniform magnetic field along and straight wire, we can simplify to:

$$\mathbf{F} = I\mathbf{L} \times \mathbf{B} \tag{2}$$

F: Force vector felt by wire
I: Current through the wire
B: Magnetic field vector
L: Length of the wire exposed to the magnetic field.

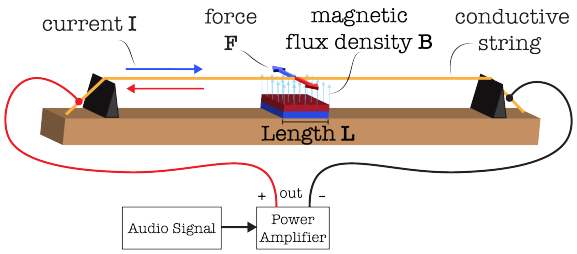


Figure 2: Lorentz force actuation – a wire in a magnetic field feels a force when carrying an electric current

This is the same underlying principle used by dynamic coil speakers but with a geometric rearrangement. Instead of a coil placed over a fixed permanent magnet, one can imagine the coil has been unwound and placed under tension across a nut and bridge. Another close analogy is the ribbon speaker, though unlike speakers designed to support a wide band of frequencies, a musical string responds most strongly to its resonant frequencies that are a function of its tension, vibrating length, and linear mass density. Additionally, rather than forces being applied approximately uniformly to the vibrating element as you would expect in a typical electroacoustic transducer, force is applied only to the section(s) along the string subject to a magnetic field. Following the right-hand rule, the force felt by the string is orthogonal to the magnetic field and current (as indicated by the current, magnetic field, and force vectors in Figure 2).

The coil "unwinding" analogy mentioned above has an electrical consequence as well; electromagnetic sensors and actuators (e.g., loudspeakers, solenoids, guitar pickups) have a significant inductive property due to their solenoid geometry that cause phase lag and bandwidth limitations in signals passing through them. However, a straight, tensioned wire has no significant inductance to resist changes in current, so current through the string can change direction quickly and support audibly higher frequencies and exhibit less magnetic coupling to nearby elements.

3.2 Sensing: Electromotive Force (Faraday's law & Lenz's Law)

To sense the string's motion, we rely on the electromotive force described by Faraday's Law and Lenz's Law. Faraday's Law describes the induced electromotive force (or *EMF* - a voltage) induced by the string's velocity in a magnetic field, while Lenz' law describes the polarity of the induced current and voltage (Equation 3 and Figure 3).

$$\varepsilon = \int (\mathbf{v} \times \mathbf{B}) d\mathbf{l} \tag{3}$$

Assuming a uniform magnetic field along L, we simplify to:

$$\varepsilon = (\mathbf{v} \times \mathbf{B})\mathbf{L} \tag{4}$$

ε: Induced electromotive force (Volts)
v: Velocity perpendicular to magnetic field
B: Magnetic flux density
L: Length of the wire exposed to the magnetic field.

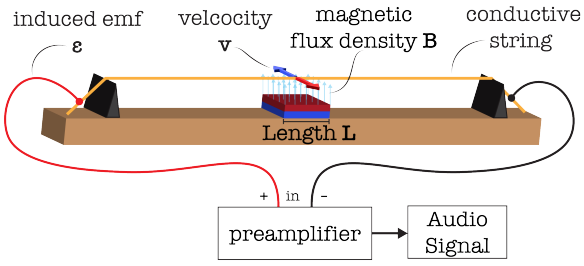


Figure 3: Electromotive force sensing - a voltage induced in a vibrating wire in a magnetic field

As seen by equations 3 and 4, the induced voltage (ε) is proportional to the velocity (**v**) and magnetic flux density (**B**). Just as Lorentz force is analogous to dynamic coil loudspeakers, EMF sensing is analogous to dynamic coil microphones. This method of string vibration sensing is well known to music researchers and practitioners [12, 34, 37, 38, 40] with some commercial systems on the market as well[3].

Though the string may vibrate on two axes, the vibrations sensed in this arrangement are only those that are orthogonal to the applied magnetic field.

3.3 Collocated Sensoriactuation via Time Division Multiplexing

Inspired by Paul Vo's now-expired patent [22], we borrow the concept of Time Division Multiplexing to bridge EMF sensing and a Lorentz force actuation.

The lower left of Figure 4 shows the order of events that occur within each frame of TDM. The processor switches between two circuits simultaneously connected to the string at a high, predetermined frame rate. Just like an audio sample rate, this

[3]https://www.stringamp.com/stringamp/

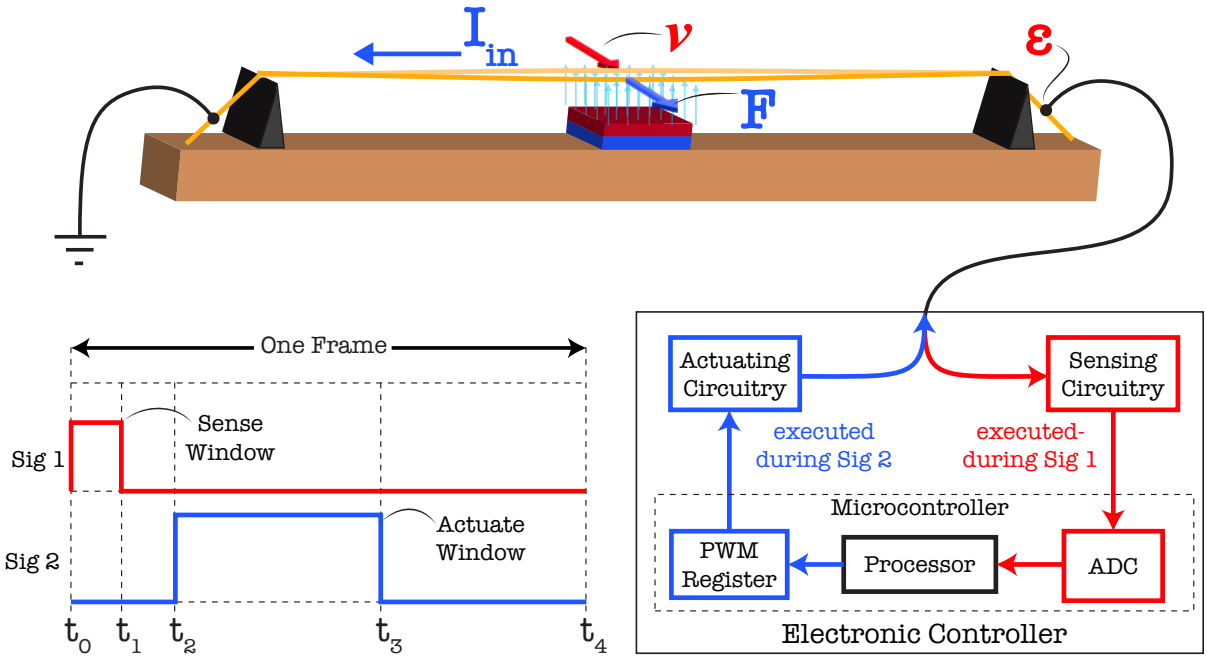


Figure 4: Sensing (red) and actuating (blue) events are interleaved within each frame (bottom left). Hardware bridges the processor to the physical string via two pathways (bottom right).

frame rate can only sense and actuate frequencies up to half of the frame rate (Nyquist Theorem). Within each frame, the system first senses the velocity of the string in one moment (during signal 1) and applies a current to the string in the next (during signal 2). At t_0, the sense event begins, and the string's velocity is sampled and stored by the controller. This conversion takes place during t_0 to t_1. Between t_1 to t_2, the system assesses the sample to determine the characteristics of actuation to be applied back onto the string. Between $t_2$and t_3 the controller has the opportunity to push current through the string, giving the string a small kick. Time t_3 to t_4 is reserved as settling time of the system, allowing the applied actuation signal in the string to dissipate from the string so that the only voltage present is generated by EMF from the string's vibration in a magnetic field. At t_4, the period ends and we once again sample the velocity of the string (t_4 of frame one = t_0 of frame two).

4 Technical Implementation

We have successfully recreated Paul Vo's 1999 patent [22] but rather than using an electromagnetic coil as a sensoriactuator (as done in the Moog Guitar), we use the alternate Lorentz force arrangement of a conductive wire and permanent magnets. Here we outline the technical hardware and software design of the current system, building on the principles of operation from above. Finally, we verify the efficacy of the system and demonstrate how the need for compensation methods has been eliminated before moving on to two musical instrument case studies.

4.1 Mechanical Setup

For this section, we consider the case of a simple monochord: a brass string is stretched across a bridge and a nut on a hard maple plank, terminated by a nail on one and tensioned with a zither pin on the other (as represented in Figures 2, 3, & 4). Permanent neodymium magnets are placed below the vibrating portion of the string, and two electrical leads from the LTDM controller are clipped directly to the termination points of the string.

4.2 Teensy 4.1 for TDM

A Teensy 4.1 microcontroller (MCU) is used as the backbone of this feedback controller, chosen for its highly reliable and manipulatable FlexPWM timers, built-in high resolution analog-to-digital converters, and the high computational capabilities of its high-speed NXP iMXRT1062 processor. 20kHz was chosen as our frame rate as it is considered the lowest frequency that remains outside of typical human hearing range, so any switching noise should remain inaudible. According to Nyquist Theorem, a sample rate of 20kHz limits our system to sampling up to a maximum of 10kHz. While this frame rate could be increased, higher rates limit the amount of time the CPU has to calculate the actuation force. In practice, acoustic instrument strings do not exhibit much significant harmonic content above 10kHz, so this sample rate seemed appropriate. Referring back to Figure 4, we now know the length of each control frame is 50μs (t_0 -t_4), granting the ADC approximately 5μs to acquire and store each sample (t_0 -t_1), the Processor another 5μs to calculate the length of the actuation pulse (t_1 -t_2), a maximum of 20μs to apply a current (t_2 -t_3), and 20μs to settle (t_3 -t_4). The actuation current is applied for a variable length of time in the style of Pulse Width Modulation (PWM)

The fully addressable 16-bit FlexPWM Modules on the Teensy 4.1 create the synchronized and reliably interwoven events seen in Figure 4 that regularly sample the string's velocity, trigger calculations, and drive the actuating circuitry. Directly manipulating these timers allows the processor to conduct real-time sample-by-sample operations during the actuation events with ample headroom for higher level control.

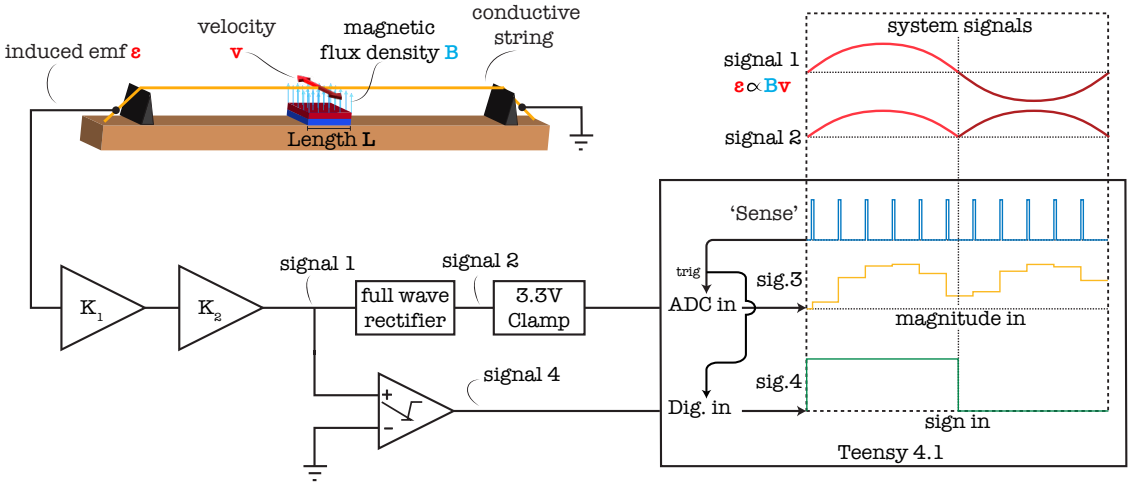


Figure 5: An implementation of EMF Sensing using analog amplification and conditioning for an MCU

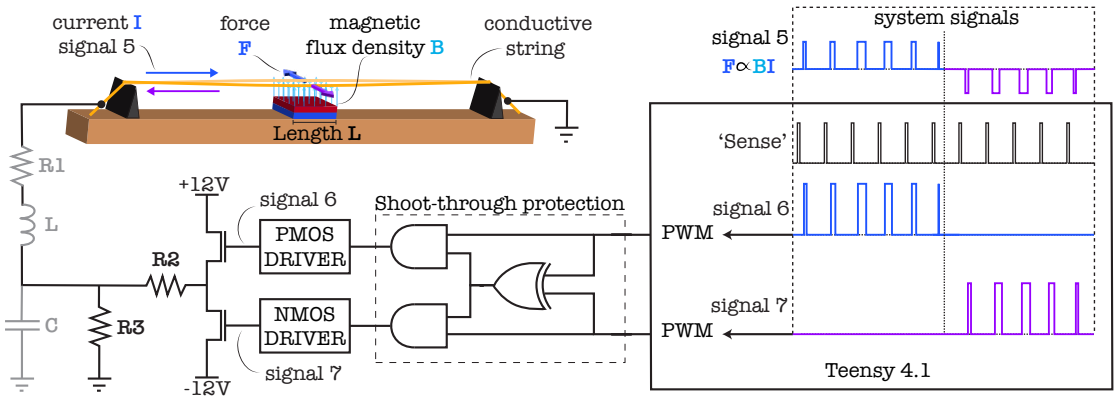


Figure 6: An implementation of PWM-style Lorentz force actuation driven by an MCU

4.3 Sensing: Multistage Preamplifier + Full Wave Rectifier + Comparator

The circuit in Figure 5 is used to monitor the magnitude and direction of the string's velocity by amplifying and pre-processing the voltage induced across the string (Equation 2). In practice, even with reasonably large permanent magnets, the expected voltage induced across the string is in the microvolt to millivolt range. For an improved signal-to-noise ratio and to maximize the dynamic range of the MCU's ADCs, it is beneficial to amplify this signal. An ultra-low noise amplifier consisting of cascaded non-inverting op amps (OPA1612) measures the voltage across the string with a gain of 250-500 [37]. In theory, the output of the preamplifier is still directly proportional to the velocity of the string in the permanent magnet's field.

The output of this preamplifier (signal 2 in Figure 5) is bipolar, meaning we see both positive and negative voltages come from the output depending on which direction the string is moving at any given moment. However, the ADC on the Teensy 4.1 is only capable of measuring voltages from 0V to 3.3V. To remedy this, the velocity signal goes through precision full wave rectifier circuit that outputs the absolute value (magnitude) of the signal, followed by a protective clamp circuit to ensure the signal connected to the MCU pin never exceeds 3.3V (signal 4). In parallel to this, the original bipolar signal is passed through a comparator that outputs either a 0V or 3.3V signal depending on whether the bipolar signal is above or below 0V (signal 5). The MCU then reads both the magnitude signal and sign signal separately and no information about the signal should be lost.

4.4 Actuation: Pulse Width Modulation via MOSFETs

To actuate the string, we use a pair of complimentary MOSFETS in a push-pull setup that can run current through the string in either direction (Figure 6). When the PMOS is activated, a +12V power supply is connected through the string to ground, and when the NMOS is activated, a -12V power supply is connected through the string to ground. Following the right hand rule, the force vector felt by the string is orthogonal to the applied magnetic field and direction of current (Figure 6).

We are running a Pulse Width Modulation (PWM) scheme where the length of the actuation pulse (i.e., duty cycle) is proportional to our desired actuation strength. After the MCU samples the string's velocity, it then determines which MOSFET to pulse on and for how long during the allotted actuate period.

In Figure 6, R1 models a string's internal resistance, which varies by string diameter, length, temperature, and material. R2

is a current-limiting resistor (usually 1Ω or 2Ω) that helps avoid strain on the power supplies and bulk capacitors. Although this resistor reduces the current through the string and lowers our maximum actuation force, it ensures safe operating currents and temperatures, especially in cases where the string's resistance is particularly small (≤0.1Ω). L represents stray inductance of the string and leads connected to it, and C represents parasitic capacitance of the load. These two values form an LC tank that oscillates at the beginning and end of an actuation pulse which can cause ringing that can destabilize the feedback system. R3 is a power resistor that helps dissipate this electrical ringing. The lower value R3 is, the faster the ringing can be dissipated, and therefore the longer we can actuate the string within each frame before the ringing creates electrical crosstalk in the next sensing frame. However, if R3 is too low, then much of the actuated pulse force can dissipate directly through this resistor instead of the string and reduce our maximum actuation force. Through simulation and experimentation, using a value in the range of 100Ω-680Ω stabilizes feedback without sacrificing too much actuation force.

4.5 Custom Printed Circuit Board

We designed the system based on Vo's patent [22] in conjunction with the theory and circuits above. Putting these concepts together, we prototyped a 2-channel LTDM system (Figure 7). On the LTDM PCB, there are connections to reroute signal flow within and out from the board for testing and measurement. The 'send' jack can send the sensed signal to guitar pedals, eurorack modules, and other outboard gear, and the 'return' jack allows the use of any arbitrary signal source as an actuation signal.

4.6 Interaction Design

The role of firmware running on the Teensy MCU described thus far has been related to the precise timing and interrupt routines necessary for interfacing with hardware, minimizing latency, and mitigating crosstalk to enable TDM. For the most simple case of feedback-actuated infinite sustain, we take the value of a sensed velocity and linearly map that to the duty cycle of the actuation pulse. However, we also wish to have higher-level control of the quality of feedback, such as overall volume or timbre. Initial use of the system with the monochord and an augmented autoharp (expanded upon further in Section 5.1) led to additional refinements in firmware designed with specific musical affordances in mind.

By using a fixed gain in the feedback path, two initial issues of musical consequence emerged. The first is a matter of note onset; if the string starts at rest, then the feedback continues to remain zero. Though this can be overcome with a simple pluck or strike of the string, we began to envision musical systems and scenarios where a musician may wish to play strings by solely manipulating the electronic controller or directly handling magnets. With sufficiently high feedback gain, we reach a point where we can quickly and reliably initiate actuation of the string (presumably due to an increased noise floor or significant amplification of even the smallest perturbations). However, the second and converse issue we run into is that this high gain necessary to initiate vibration causes the string to vibrate aggressively and beyond desirable levels.

4.6.1 Noisy Actuation. We address the initial note onset issue by first adding a randomly-generated value to the actuation pulse length. This value manifests as white noise, applying actuation pulses of random magnitude and polarity to the string even when there is no detected vibration signal. When a magnet is present near the string, the wide-band actuation signal initiates resonant harmonic vibrations in the string. The issue with this is that the noise is still noticeably audible even when the string self-oscillates.

4.6.2 RMS Monitoring. The first step in addressing the audible noise is calculating the average vibrational power of the string. RMS (root mean square) is a common way to assess the average power of a bipolar voltage or current signal; As a new sample comes in every 50μs, the value is stored in a circular buffer (200 samples) and a running RMS is calculated during the non-critical moment of each frame (t_3 to t_4 of Figure 4). As the calculated RMS signal (proportional to the string's vibrational power) increases, the processor reduces the amplitude of the white noise to instead actuate primarily with feedback so no noise is heard while the string is infinitely sustained. The RMS calculation used is as follows:

$$\text{RMS} = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1} x[n]^2}, \quad \text{with } N = 200$$

S_n, the scaling factor of the noise, is then programmed to be inversely proportional to the measured RMS value yet bounded between 0.0 and 1.0. S_{RMS} is a scaling factor used to increase the weight of the RMS signal, allowing the noise to be scaled back more with a lower incoming RMS value:

$$S_n = 1.0 - S_{RMS} * \text{RMS}, \quad 0 \leq S_n \leq 1$$

4.6.3 Automatic gain control. Although this solves the issue of vibration initiation, we still have difficulty finding the balance between the string's vibrations feeling too slow to build up versus becoming too loud and overpowering. Using the same RMS value calculated above, this value can be compared to a target RMS value; if the string's vibrational power is measured below the target RMS value, the controller increased the feedback gain to allow vibrations to build up more quickly. If the string is vibrating above the target RMS value, the controller will reduce the feedback gain. This dynamic feedback gain clamps the string's vibrational power to a desired target value when magnets are present, acting more or less as an overall volume control. This scheme yields somewhat predictable and repeatable interaction the string while maintaining the gesture-controlled and tactile response of a physical string.

4.6.4 Active Damping. Active damping is the opposite case to infinite sustain; rather than continually adding energy to a string to support harmonic vibrations, negative feedback can be used to actively oppose vibrations (Figure 8). This is achieved by reversing the polarity of the actuation signal that we previously used for a simple sustain. Informal experiments suggest our system is capable of active damping to some degree – shortening the decay time of a plucked string so that it stops vibrating sooner than if it were under passive conditions. Though we have seen moderate success in active damping, performing this with LTDM is inherently limited because the LTDM system only senses velocities and applies forces on one of the string's two axes [3].

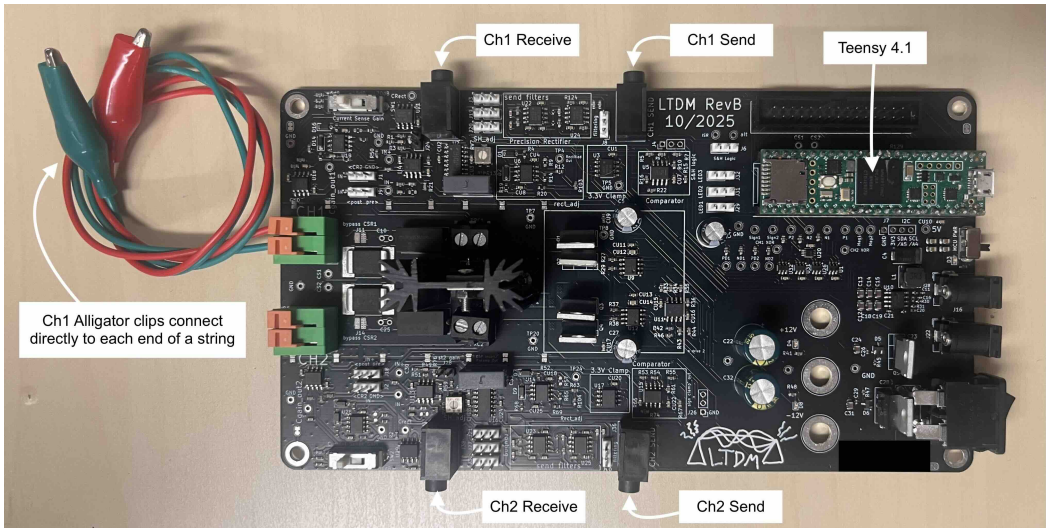


Figure 7: Custom 2 channel LTDM PCB powered by Teensy 4.1

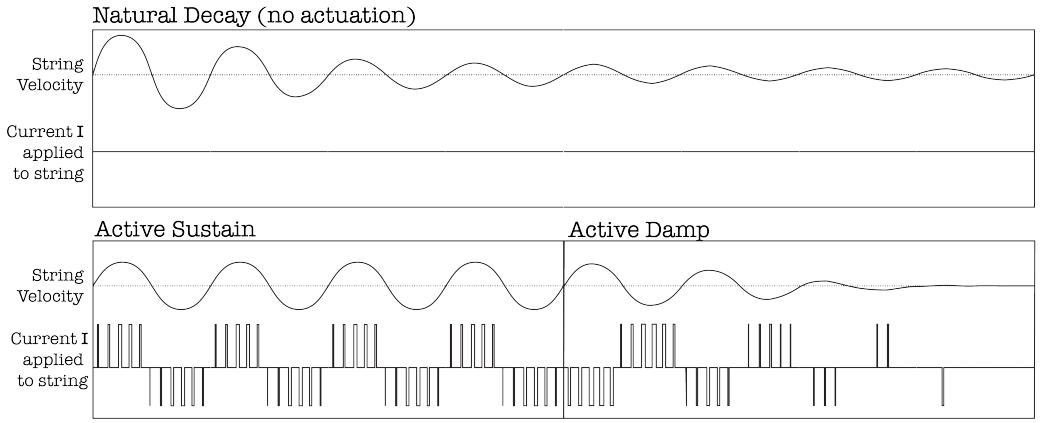


Figure 8: String under passive (top) and active (bottom) conditions

5 Case Studies

Here we highlight LTDM in two case studies with contrasting sonic results. This contrast arises from differing mechanical arrangements and playing techniques – the circuits and software remain the same between instruments.

5.1 Augmented Autoharp

The first case is an augmented autoharp (Figure 9). When designing the LTDM system, we assumed each string would require its own channel on the PCB, limiting us to only two strings with one two-channel PCB. However, by replacing the metal bridge and nut that the strings rest on with short segments of conductive rod long enough for two adjacent strings to rest on at once, we were able to arrange the strings so they all make up a single, continuous electrical path, allowing us to connect multiple strings to a single channel of the PCB (Figure 10). By connecting the LTDM system to just two points, several strings are electrically in series and the strings that decide to feedback are directed by the positions and gestures of handheld magnets. This instrument is used in the 2026 alt.nime work *Connecting to Ground: A Séance in the Wick Woodlands* [23].

5.2 The Weather Harp

In 2025, a collaboration began with University of Michigan professor Michael Gurevich and PhD student Molly Jones using our LTDM technology. Together we have been co-developing a musical instrument called the Weather Harp (Figure 11), which was initially inspired by the wind-actuated aeolian harp but replaces the unpredictable and untameable wind with our own controllable electromagnetic actuation method [18]. The instrument has manifested as an augmented bass drum, featuring brass strings stretched across the drum's frame and coupled to the drum's membrane with a hand carved wooden bridge. Magnets are fixed to the drum's head and drum frame rather than handheld, and the instrument is considered "self-playing", driven by a live stream of weather data rather than by a live musician. The physical complexity of the instrument supports nonlinear and unpredictable sounds that are still eerily cyclical and musical in nature.

The instrument is central to an interactive sound installation exploring agency, control, and non-linearity, touching on many of the themes outlined by the Feedback Musicianship Network and contributing to the growing body of work in this space [36].

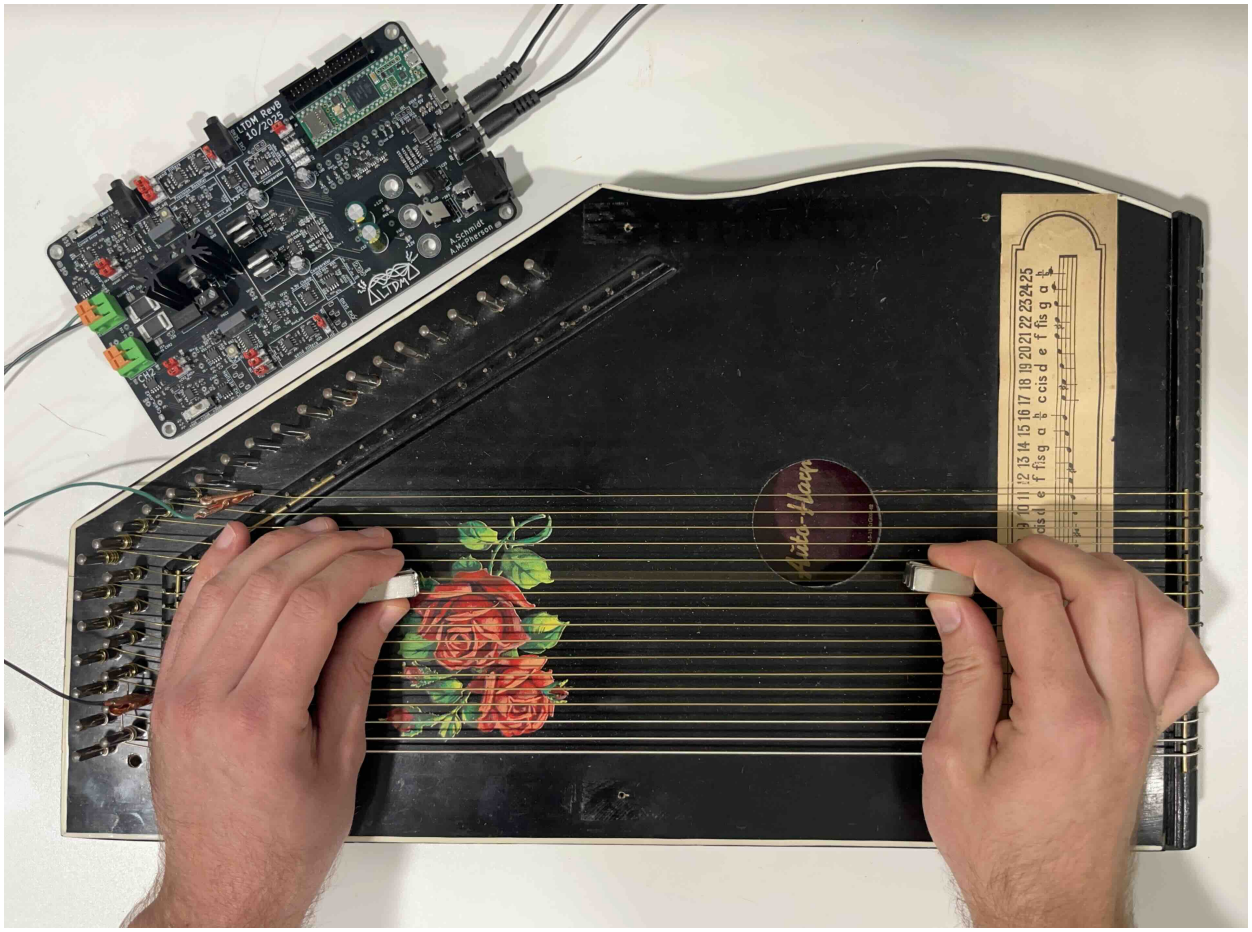


Figure 9: Augmented Autoharp connected to the LTDM PCB

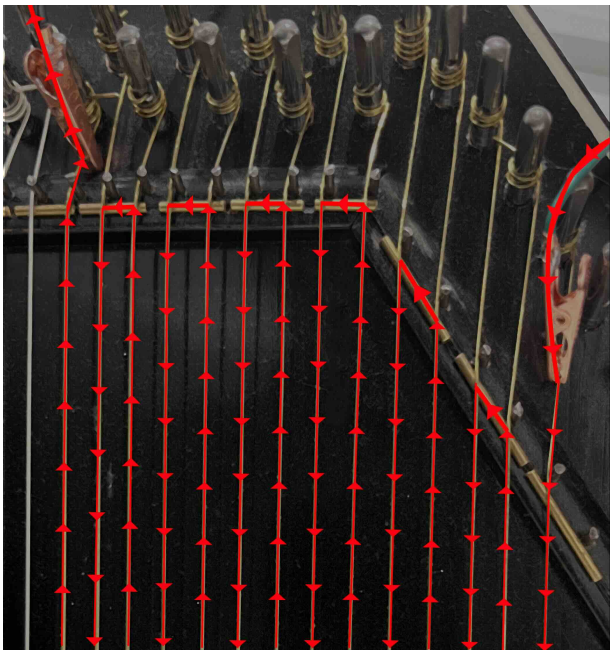


Figure 10: Electrical pathway through all strings



Figure 11: The Weather Harp - a four channel actuated string instrumented built from a bass drum frame

5.3 Contrasting Sounds

It is trivial to add a feedback system on top of an existing instrument that more or less act independently (e.g., an eBow + a piano string), but it is more interesting – and much more challenging – to create a feedback network that explores and exploits the unique interactions that emerge between the physical, electrical, and digital realms. Systems such as this are typically complicated to deploy due to instrument-specific control schemes that rely on precise calibration, sensitivity to sensor and actuator placement, and computationally expensive DSP. However, LTDM begins to take a step in the direction towards a system that reduces this design bottleneck because energy is exchanged between physical and digital domains through the collocated control scheme. The firmware and electronics require no calibration or prior knowledge of the physical system it is actuating; the same PCB running the same firmware power both the Autoharp and Weather Harp, yet each has distinct behavior due to physical arrangement. In the case of the Weather Harp, its design brings out physical and electromagnetic nonlinearities and sympathies between strings, drum membrane, and magnets without explicit programming [18]. In the case of the augmented autoharp, the predictable and causal response from the sturdy acoustic box and regularly-spaced strings means a user's gestures with handheld magnets becomes the main gateway towards invoking and controlling instrument behavior. Video examples of these two contrasting LTDM instrumenets can be found on the accompanying github repo: https://github.com/aschmidt99/LTDM_NIME2026.

6 Discussion

Musicians seeking rich sonic textures praise feedback instruments for their unpredictability and chaotic behavior - hallmarks of feedback musicianship [19, 28, 31, 32]. However, it makes structured performance and predictable instrument behavior a challenge. Meanwhile, commercial music technology often prioritizes control and causality, often associated with quantization and rigid, grid-locked parameterization in Digital Audio Workstations (DAWs) and the Musical Instrument Digital Interface (MIDI) protocol. This minimizes the influence of physical factors on instrument behavior and sacrifices much of the potential for nuance and naturally-occurring nonlinearities found in acoustic instruments and instead emphasizes repeatability and predictability in music.

6.1 Affordances

We feel LTDM offers a balance between these extremes. At present, our collocated sensoriactuation system has opened the doors for simple deployment of feedback actuation as well as elegant transformation of acoustic and electromechanical instruments, recontextualizing and revitalising them with minimally invasive augmentations that reap the affordances of both Lorentz force actuation and TDM as well as highlighting some unique characteristics of their simultaneous implementation.

6.1.1 Simple deployment. For instruments that have electrically-isolated strings (not shorted through a conductive bridge, nut, or other hardware), LTDM is simple to deploy and can be quickly connected and disconnected to strings for rapid prototyping. Rather than carefully fixing solenoid actuators near strings or being burdened with many wires, the barrier to entry is simply sorting the electrical path through the strings and fixing or holding a magnet near them. With LTDM, the practitioner becomes largely free from calibration, measurements, calculations, transfer functions, or any other complex math or models, affording them simple and rapid reconfiguration between instruments with the focus of designing feedback instruments now shifting towards teasing new sounds out of the materials and mechanical properties of an instrument.

6.1.2 Holding, fixing, or moving magnets. LTDM grants flexibility in how one interacts with a string. For a keyboard-style instrument, it may make the most sense to fix the magnets to a soundboard or rail, and whether or not the strings are actively being actuated can be determined by a hardware controller, a digital GUI, or a physical mechanism. In contrast, the designer may find interest in manually holding and manipulating magnets (as suggested by Figure 1 and Figure 9).

6.1.3 Harmonic access. With LTDM, the entire vibrating length of a string becomes eligible for collocated sensoriactuation, so manually moving magnets or using multiple magnets affords the targeting and evocation of vibrational modes and timbres that other feedback methods cannot easily access. Higher frequencies are more accessible to Lorentz force actuation than coil-based actuation due to the low inductance of a straight wire [27, 42]. Upper partials of the vibrating string can be accessed using multiple magnets with opposite polarities facing the string (again suggested by Figure 1). From an actuation mechanism standpoint, the string is 'pulled' at one point of the string and 'pushed' at another, potentially inducing anti-nodes at the positions where magnets are. From a sensing standpoint, the EMF-induced voltage is the sum of multiple velocities in multiple magnetic fields that interfere constructively and destructively on the string. For Figure 1, even if the fundamental frequency was present, it would be approximately canceled out in the 'picked-up signal' and begin to favor the second harmonic.

6.1.4 Active Sympathetic Vibrations. One unique characteristic of LTDM is the ability to excite one vibrating string and use its signals (both sensed and actuated) to excite another string within the electrical path. This is similar to sympathetic vibrations that naturally occur on acoustic or electromechanical instruments, but now we can amplify and steer sympathy within the system with magnet positions. It affords the user the feeling that they can selectively "pick up" a vibration at one point on the instrument and "drop it" somewhere else in the system. We are calling this empathetic vibration, emphasizing that the strings are not just feeling a passive, mechanically induced vibration, but rather are actively electromagnetically engaged with one another.

6.1.5 Material-driven design. The LTDM system thus far exhibits rich and emergent behavior with evolution of sound that depends on interactions between the material, mechanical, acoustical, and electrical properties of an instrument or system. This contrasts to many existing actuated instruments where actuation signals are designed or conditioned to behave within the context of a particular instrument manifestation. The design of an instrument can evoke different behaviors; in the case of the autoharp, the fixed bridge produces stable and predictable behavior, whereas mechanically coupling strings to resonant membrane like the weather harp evokes more chaotic and emergent behavior from the same type of brass strings.

6.2 Limitations

We have observed different sensing, actuating, and feedback limitations in LTDM broadly as well as specific string materials. Here we discuss some limitations to create practical guidelines for instrument construction and electronics design.

6.2.1 Control axes. Inherent to Lorentz force actuation is the limitation to only affect one axis of string movement at a time. For a higher level of control over a string, Paul Vo's Moog Guitar and Vo-96 systems use two electromagnetic coils tilted 90° to one another to act on each of the vibrating axes of a ferromagnetic string [22]. Since LTDM actuates with a single current that goes through the entirety of the string at any given moment, multi-axis control is not an option. Two permanent magnets can indeed be positioned 90° to one another, though the sensed signal is flattened into a single signal and information about which magnet contributed to which part of the signal is lost. This is not a major limitation for sustain systems but limits the efficacy of an active damping scheme (as mentioned in Section 4.6.4).

6.2.2 PWM power bottlenecks. In our implementation, the maximum actuation period for our 20kHz framerate (50μS period) is set to be 20μS (or maximum 40% duty cycle). This means for a 24W power supply for the actuation circuitry, the maximum effective power that can be used for actuation is approximately $24W * 40\% = 9.6W$ [15]. Furthermore, the sharp edges of these high-frequency pulses contain ultrasonic harmonics that electrically contribute to heat buildup but do not contribute to actuating the string in a meaningful way.

6.2.3 Audio processing without conventional DSP. The audio samples cannot go through sample buffers for processing without compromising the collocated control, which eliminates the use of most audio Codecs. The Teensy audio library is convenient and powerful, but interfacing from the Teensy's NXP iMXRT1062 to external hardware will incur latencies that could destabilize the system or add complexities.

6.2.4 Ferromagnetic strings. Strings made of ferromagnetic elements (iron, cobalt, or nickel) or alloys of these materials exhibit behavior much different to non-ferromagnetic strings due to forces from the necessary magnetic field pulling directly on the string, causing dissonant, non-harmonic overtones. This effect is known to electric guitarists as *stratitis* and often considered undesirable in musical contexts.

6.2.5 Thermal expansion down-tuning. Metal strings exhibit electrical resistance dictated by their length, diameter, material composition, and temperature. As current is run through a string, the resistance of the string induces a voltage drop across it. Following Ohm's Law ($V = I * R$), this voltage is a product of the current run through the string and the resistance of the string, and following the power equation for electric circuits ($P = I * V$), we know that power is dissipated in the string itself. Much of this power dissipates as heat, which in turn can cause thermal expansion of the string, causing the string to lengthen. When the string is held in tension by friction (like a standard guitar-style tuner or zither pin), the increased length of the string reduces its tension and lowers its pitch. This effect can be interesting, but in many musical contexts with fixed scales, stable tuning of the instrument is of high priority.

Brass (both red and yellow) has been the best performing material thus due to its high conductivity and lack of ferromagnetic effects. Steel and iron can work but suffer significant detuning [42].

6.2.6 Tension-induced Up-tuning. We have also heard the tuning of a string drift upwards rather than downwards. This is because LTDM is sometimes able to drive a string hard enough that its average tension increases and causes the string to vibrate at a slightly higher frequency than what you would hear from a pluck or strike. The fact that the initial onset of a string pluck or strike rings sharp is well known to stringed instrument players and is more prominent as string tension is lowered.

6.2.7 An unknown effect. We have seen several string materials work with our system, though the most puzzling result thus far occurs with copper-wound or bronze-wound steel core strings. Although the system can sustain vibrations in bronze strings, brass strings, or steel strings independently, steel wire wrapped with copper or bronze windings pushes the LTDM system into an unstable oscillatory state related to the TDM switching frequency, manifesting as an audible squeal at 10kHz, 5kHz, or 2.5kHz when our sample rate is 20kHz. Although wrapping steel with wire initially sounds similar to an inductor, this is not electrically equivalent because the windings are typically electrically connected to the string core wherever they touch and thus produce no significant inductance.

7 Conclusion

This research aims to push forward a new generation of musical instruments and practices and contribute to the subculture of feedback actuated instruments. Our system thus far exhibits rich and emergent behaviors that depends on interactions between the material, mechanical, acoustical, and electrical properties of an instrument. Future work includes refining and developing technology and conducting experiments to deepen our scientific understanding of feedback systems and collocated control.

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.

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