The Magnetochord: A New Electromagnetic Feedback Musical Instrument

Adam Schmidt
Dyson School of Design Engineering
Imperial College London
London, UK
a.schmidt24@imperial.ac.uk

***Abstract*—This work proposes the Magnetochord, a new electromagnetically-actuated instrument that uses our recently-developed Lorentz Time Division Multiplexing (LTDM) feedback control scheme. Though many feedback instruments depend on using separate, external sensors and actuators to monitor and induce vibrations in a string, our electronic controller initiates and sustains vibrations by running electric current through the string itself, causing strings to self-sustain when a permanent magnet is held in close proximity and enabling a new playing technique from the same metal strings musicians have used for centuries.**

I. Introduction / Background

We have recently 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* [21][22], creating what we call Lorentz Time-Division-Multiplexing (LTDM) [23]. 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 and a recent commercial uptake of electromagnetic feedback instruments, this work paves the way for a new class of musical instruments.

Rather than striking, plucking, or bowing a string to create sound from a musical instrument, LTDM allows us to inject energy into a string without physically touching it. String vibrations can be indefinitely sustained via our hardware controller with just a pair of electrical leads and a permanent magnet. Our design has a similar motivation to many prior works in the feedback instrument space; to expand the sonic palette available to a musical instrument player. However, our implementation bypasses some of the design bottlenecks of prior feedback actuation methods and allows the instrument designer 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.

II. Related Work

Although digital sound synthesis has dominated recent decades, musicians are rediscovering the richness and physicality of acoustic sound production. Electromechanical instruments with physically moving parts such as the Fender Rhodes and Hammond Organ are prized for their responsive materiality and physical presence [6][14][16], and new commercial electromechanical [1] and feedback-actuated [2] instruments continue to emerge.

Feedback-actuated instruments are instruments that use sensors to actively monitor the vibrations of the instrument – the sensed signal is then used to drive an actuator and actively contribute vibrations in the system. A classic style of feedback-actuated instrument uses feedback to resonate its sound-producing elements indefinitely (also known as *infinite sustain*). Many feedback instruments use magnetic coils in the form of solenoid electromagnets, vibration transducers, or cone loudspeakers to induce physical vibrations in a resonating body [10][15][18][20][24][25][26]. *Lorentz force actuation* is an alternative electromagnetic actuation method whereby force is applied to a conductive wire by running an electric current through it while exposed to an external magnetic field [13][21][22][23]. 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 [9][17][19].

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 [1][2][3][4][5][11].

Finally, a transducer used as both a sensor and actuator simultaneously can be referred to as a *sensoriactuator* [7]. To

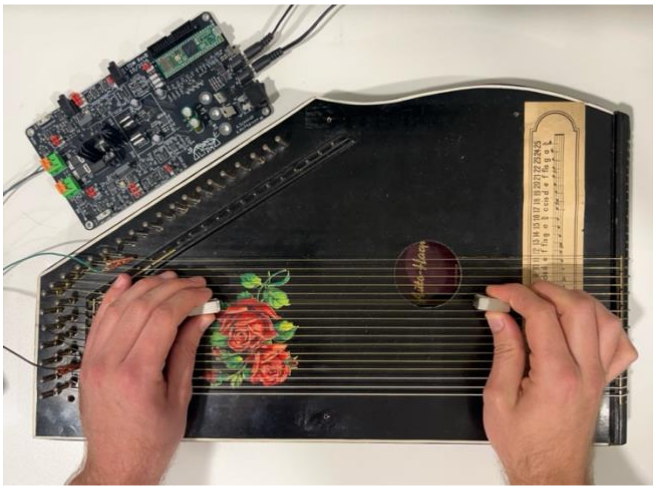
[1] https://gamechangeraudio.com/motor-synth-mkii; https://circleinstruments.com; https://murobox.com

[2] https://korg.berlin/products/phase8, https://www.physical-synthesis.com

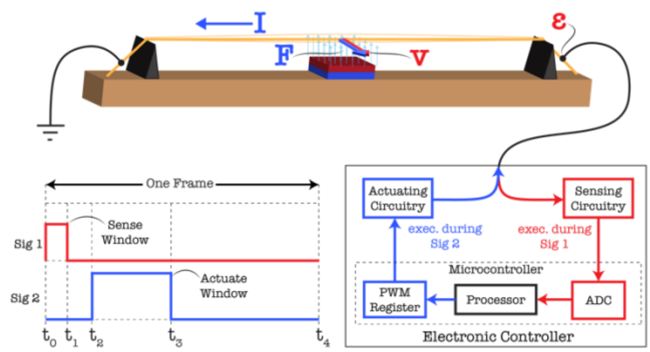
achieve collocated control, the sensing and actuating mechanisms must be isolated to prevent unwanted electrical crosstalk between the sensing and actuation signals. Our recent work describes how this can be achieved by a hardware controller that rapidly switches the transducer between sensor and actuator roles - also known as time-division multiplexing [8][23].

III. Imagined and Existing Prototype Sketches/Drawings/Photos

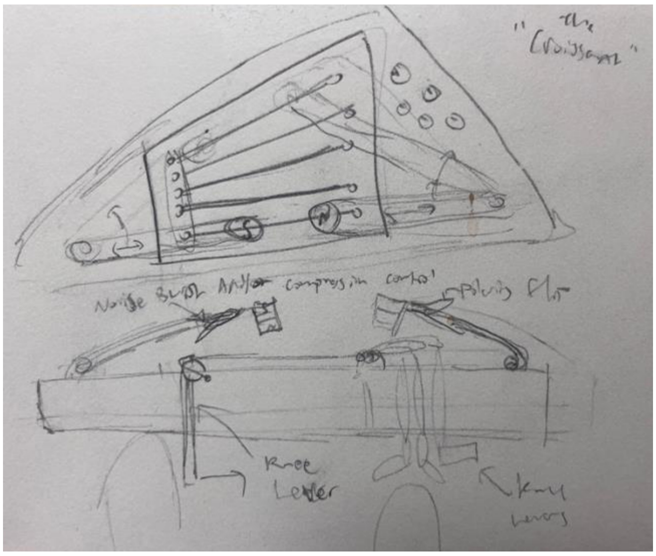
The current prototype of the Magnetochord exists as our hardware controller paired with an augmented autoharp. The hardware controller (known as the 'LTDM Kit') has been developed for prototyping ideas quickly and flexibly at the workbench but has yet to be optimized for cost and formfactor. Circuit designs were first prototyped on a breadboard and/or simulated in LTSpice before being captured and laid out in KiCad. PCBs were manufactured and assembled by JLCPCB, and enclosure for the PCB was designed in Fusion 360 and 3D printed. The system runs on Teensy 4.1. A video demo of the system can be found here: https://youtu.be/dVcz-NvMx0Q



The design works by rapidly alternating (at 20kHz) between sensing circuitry and actuation circuitry to create a feedback loop that sustains string vibrations depending on the position of handheld magnets. Refer to the appendix (Section VII) for the sensing/actuating concepts and circuitry we are using.



This autoharp and LTDM Kit combination has been great for prototyping, but we envision a new instrument form factor more ergonomic for this playing technique, such as larger spacing between strings, knee levers for pitch-bending strings, or small arms that allow the musician to hold magnets more steadily and leave them in a fixed position. We hope this new instrument will integrate the electronics seamlessly within the instrument rather than being external.



IV. Responsible Innovation

Although this proposal focuses on a new instrument, this technology offers the unique opportunity to repurpose existing instruments, like in our example of the vintage autoharp. The hardware kit can be connected to any string instrument so long as the strings ae conductive, offering new sounds by upcycling existing instruments found in the nooks and corners of charity shops, attics, or eBay. Furthermore, the firmware for the LTDM controller is open-source, offering users of the hardware the opportunity to program new actuation and feedback behavior on their own in the open-source spirit.

V. Author Bio(s) / Experiences

Adam Schmidt is a PhD Student at Imperial College London's Dyson School of Design Engineering working on designing electromagnetically actuated instruments under the direction of Professor Andrew McPherson in the Augmented Instruments Lab. He received his bachelor's in Sound Engineering and Electrical Engineering and master's in Performing Arts Technology from the University of Michigan. His research investigates how vibrations within instruments can be augmented via electronic feedback and alternative transduction methods. Lately he has been focusing on Lorentz force actuation in instruments such as the Lorentz Lap Brass with Michael Gurevich [21] the Sparksichord with Jeff Snyder and Andrew McPherson [22], and the Weather Harp with Molly Jones and Michael Gurevich [12]. A paper outlining the LTDM control scheme is forthcoming [23]. His key skills are in electronics design and prototyping (system design, KiCad schematic capture and PCB layout) and physical prototyping (CAD, 3D printing, CNC machining, and woodworking).

VI. Acknowledgements

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VII. Appendix

Concepts, equation, and circuits used for sensing and actuating are provided in this appendix for additional context.

A. Sensing Concept: 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 *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 1 and Figure 1).

$$\varepsilon = (\mathbf{v}\times\mathbf{B})\mathbf{L} \qquad (1)$$

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

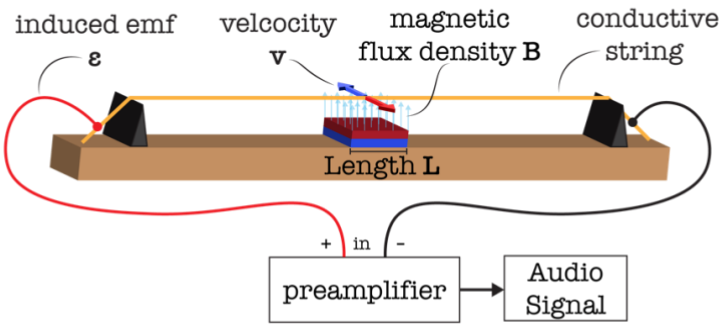

Figure 1: Electromotive force sensing - a voltage induced in a vibrating wire in a magnetic field

B. Actuating Concept: 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).

$$\mathbf{F} = \boldsymbol{I}\mathbf{L}\times\mathbf{B} \qquad (2)$$

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

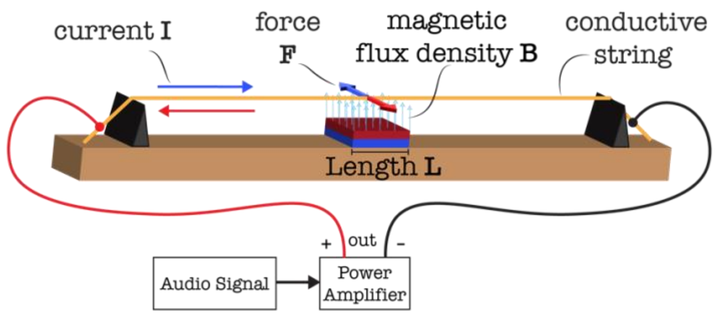

Figure 2: Lorentz force actuation – a wire in a magnetic field feels a force when carrying an electric current

C. Sensing: Multistage Preamplifier + Full Wave Rectifier + Comparator

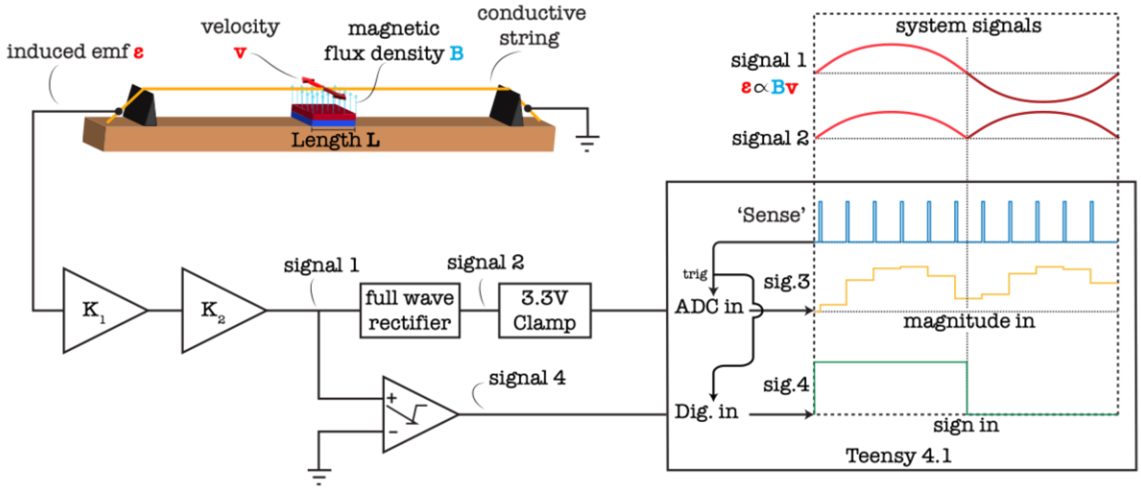

Figure 3: An implementation of EMF Sensing using analog amplification and conditioning for an MCU

The circuit in Figure 3 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 1). 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 **Error! Reference source not found.**. 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 1 in Figure 3) 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. 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.

D. Actuation: Pulse Width Modulation via MOSFETs

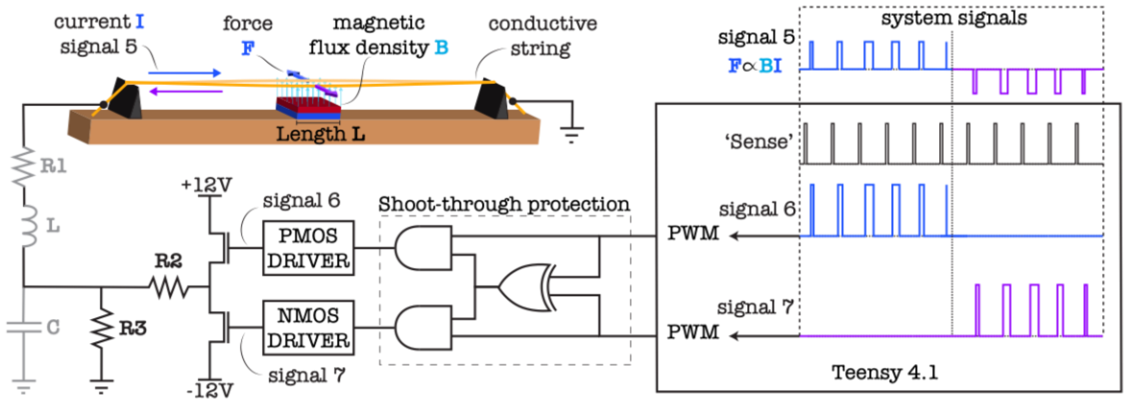

Figure 4: Our implementation of PWM-style Lorentz force actuation driven by an MCU

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 4). 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 4).

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 4, 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.