The Hummellaphone: An Electromagnetically Actuated Instrument and Open-Source Toolkit

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ABSTRACT

This paper presents the Hummellaphone, a highly reconfigurable, open-source, electromagnetically actuated instrument being developed for research in engineering learning, haptics, and human-computer interaction (HCI). The reconfigurable performance interface promotes experimentation with gestural control and mapping. Haptic feedback reintroduces the tangible bidirectional communication between performer and instrument that is present in many acoustic and electro-acoustic instruments but missing in most digital musical instruments. The overall aim of the project is to create an open-source, accessible toolkit for facilitating the development of and research with electromagnetically actuated musical instruments. This paper describes the hardware and design of the musical instrument and control interface as well as example research applications.

Author Keywords

electromagnetic actuation, mechanical synthesis, human-computer interaction, haptics, sustain, hardware

CCS Concepts

•**Human-centered computing** → **Interaction design process and methods;** •**Hardware** → *PCB design and layout;* •**Applied computing** → *Sound and music computing;*

1. INTRODUCTION

This project was largely inspired by the technology integrated within the Moog Guitar, and prompted by direct conversations with its designer, Paul Vo. After our prior experimentation with embedding sustainer technology into an electric guitar, Vo advised that recreating the technology in the Moog Guitar from its underlying patent [12] would be instructive, noting that there would be no restrictions on recreating it as the patent has expired.

An initial response to Vo's challenge led to a realization of a self-sustaining, custom built one-string guitar, which informed the development of the current project. Specifically, it prompted consideration of whether the same technology could be more successful if implemented in contexts other than the guitar. The Moog Guitar was not especially successful in terms of widespread adoption or commercial sales (the original list price was $6495 USD). Motivating questions became:

1. Could we design an entirely new electromagnetically actuated sustaining instrument that sheds the baggage of the existing form and techniques associated with traditional instruments?

2. What roles would reconfigurability and a lack of resemblance to traditional instruments play in promoting exploration and adoption of such an instrument?

3. Could lower cost and open source tools promote the wider adoption and creation of electromagnetically actuated sustaining instruments?

1.1 Related Work

1.1.1 Infinite Sustain & Damping

There is extensive literature on exciting and sustaining steel strings, metallic bars, and other idiophones by means of electromagnetic and/or acoustic feedback [4, 21, 6, 10]. The Magnetic Resonator Piano [16] is a notable example, in which electromagnetic coils are mounted to a grand piano to augment and extend its capabilities and performance practice. The opposite function, actively damping, is more difficult to implement, but advocated by Berhdahl et al. [3]. The Moog Guitar [12] is a rare example that is able to both actively sustain and actively damp steel guitar strings while simultaneously having active control of the harmonics present in the string's vibration. Instruments that employ electromagnetic or acoustic feedback control are most frequently augmentations of existing musical instruments. Examples of instruments developed with electromagnetic actuators from their genesis are far less common and present a rich opportunity for exploration.

Most augmentations of existing instruments involving electromagnetic actuation cited above are bespoke and unique, typically invoking high costs. The Magnetic Resonator Piano requires both a fully functional grand piano plus the substantial added cost of adding an electromagnetic actuator for each active string. Similarly, augmenting an electric guitar bears additional requirements such as miniaturizing the circuitry to fit within the guitar, additional power considerations, and maintaining the guitar's weight and balance point within an expected range.

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1.1.2 Electromechanical Instruments

Electromagnetic instruments that rely on magnetized vibrating steel to induce a signal in a pickup have been around for over a century. The Telharmonium is the most notable early example [26], and popular modern instruments in this category include the Hammond Organ, Fender Rhodes, and Electric Guitar. Bart Hopkin's What-A-Shame [11] varies the frequency of a vibrating steel rod by allowing the performer to dynamically change the length of the vibrating portion by sliding it through a narrow hole in a block of wood. This instrument features a similar pitch-changing mechanism to the Hummellaphone, but is performed more like a daxophone [7] or lamellaphone.

1.1.3 Reconfigurability

We consider two aspects of reconfigurability: *virtual* and *physical*. The first is a flexible relationship between the sound generation mechanism and the control interface. This *virtual* reconfigurablity enables users to quickly and easily map and remap inputs such as button presses, dial angles, or applied pressure to the output parameters such as pitch, filter cutoff frequency, or amplitude. This is generally made possible in the domain of DMIs because of the decoupling between physical interface and the software-based sound generation from the physical interface [27, 17].

The *physical modularity* of an interface allows users to rearrange and redesign the physical layout of the interface with ease. There are numerous examples of modular, reconfigurable interfaces that control digitally-produced sound [8, 13, 22, 24, 15], and there are also examples of research that explores benefits of the decoupling of an interface from acoustic/electromechanical instruments [20, 2, 5, 21].

In most actuated and non-actuated electromechanical or acoustic instruments, the performer's body has a direct and intimate relationship with the generated sound through plucking, pressing, bowing, etc. Consequently, making a change to how the input affects the output would involve a significant overhaul in the mechanical design of the instrument.

1.1.4 Haptic Feedback

The tactile force feedback experienced by musicians when playing acoustic and electroacoustic instruments is considered an important factor in facilitating learning and playability. There is a growing body of research that addresses the typical unidirectional communication from performer to DMI by introducing force feedback through haptic actuators, and researchers now generally agree that haptic feedback increases the intimacies between musician and instrument and can even make them easier to play [19, 28, 18, 1].

Research by Luciani et al. [14] demonstrated compelling results from using audio signals to drive the force feedback of a cello-like haptic simulation. Advancements in digitally-controlled force feedback resulted in participants expressing that the virtual string they bowed felt very real. The authors write, "the most unexpected and promising result relies on the spontaneous remark made by all the performers happily surprised by the 'strong presence of the string in hand', triggering a strong feeling of presence of the string, thanks to the never realized 44Khz audio-haptic simulation," which compared favorably to prior research with lower (3Khz) audio-haptic sampling rates. These findings motivated us to use the existing analog audio signals present in our system to drive haptic force feedback – a technique that is enabled by our analog signal processing approach [14].

1.1.5 Morphology and Modality Research

Harrison et al. note the prevalence of 'instrument-like' controllers or DMIs in NIME [25], and the suggestion in the accompanying discourse that such devices facilitate "the re-use of playing techniques from traditional instruments and hence offer a route to faster uptake" [9]. In a study attempting to unpack this assumption, Harrison et al. pose to what extent being 'instrument-like' means "sharing interaction modalities" or "having the cultural appearance that stands in for a traditional instrument [9]?" They found that the answer diverges somewhat between guitarists and non-musicians, with both the interaction modality and the cultural appearance playing a role in study participants' preferences and associations. But this limited user study was necessarily confined to short-term, constrained interactions with the example instruments, and could not investigate long-term adoption or development of performance practice. In a prior study, McPherson expresses interest in leveraging the virtuosic playing of established pianists, framing the Magnetic Resonator Piano as enabling a new repertoire of extended techniques [16]. But where a new 'instrument-like' system's affordances don't exactly match those of the acoustic instrument from which it derives, we speculate that the uptake of new 'instrument-like' systems among experts on the analogous system (e.g., adoption of the Moog Guitar by expert guitarists), in both long term and research contexts, may be equally impacted by established notions or expectations of skill, style, and technique that could lead to self-imposed barriers on exploration and development.

2. PROJECT GOALS

The motivations and tensions that emerged from the prior work discussed above prompted the development of a novel instrument that would become the Hummellaphone with the following design criteria:

1. A performance interface that is both physically and virtually reconfigurable.
2. Electromagnetic actuation of a mechanical system.
3. Audio-driven haptic feedback.
4. A relatively low cost using standard, accessible, and readily-available materials and components.
5. A novel form that is not explicitly related to any existing instruments.

In addition, we identified the two higher-level project goals:

1. An accompanying series of workshops/modules to equip musicians/engineers to understand and build electromagnetically actuated instruments, using the Hummellaphone as an exemplar.
2. Release of an open-source toolkit that consists of build documentation, reference designs, electronic and mechanical design principles, Computer Aided Design (CAD) files, schematics, parts lists, and more. An online knowledge base will provide room for discussion, results, troubleshooting, etc.

3. TECHNICAL DESIGN

In this section, we describe the initial mechanical, electronic, and software design of the Hummellaphone, a modular, reconfigurable, electromagnetically actuated instrument that was developed in response to these goals. The current design consists of four independent sound-generators, but its modular nature allows any number of additional units to be added. Each sound generator is an electromagnetically actuated steel rod supported by a bespoke roller bridge. A servo motor pushes and pulls the rod through the roller bridge to change the effective length of the rod and therefore dynamically change the pitch. Closed-loop feedback allows the instrument to compare the exact pitch of the steel rod to the desired pitch and compensate with the motor accordingly.

3.1 Electromagnetic Sensoriactuators

Electromagnetic coils act as both the sensor and actuator for each vibrating steel rod on the instrument. Initial coil prototypes have used 24AWG enameled copper wire wrapped around a cylindrical ceramic magnet. Coils are are paired up and wound in opposite directions to create a single humbucking pickup.

3.2 Electronic Hardware

The circuitry is modeled after the circuit from the Moog Guitar [12]. A detailed explanation of the schematic or component selection is out of the scope of this paper and will instead be presented in future learning modules. Instead, a simplified description is provided.

The coils are connected to a circuit that switches between sensing and actuating modes at a high frequency (>20kHz). During the sense period, the instantaneous velocity of the rod is sampled and stored. During the actuate period, a current is sent through the coil to induce a magnetic force to influence the vibration of a steel rod. The amplitude and direction of the force applied is determined by the current state of the rod, a desired harmonic profile, and the signal processing circuitry.

3.3 Harmonic Control

3.3.1 Analog Signal Processing

The Hummellaphone's actuation and harmonic control are performed entirely in the analog domain. This was initially aesthetically motivated, but has since revealed additional advantages. Early prototyping of advanced harmonic control techniques used real-time Digital Signal Processing (DSP) code exported from Functional Audio Stream (Faust) and uploaded to a Teensy 4.0. This workflow facilitates rapid prototyping but imposes signal delays inherent to DSP, which makes harmonics of each steel rod more difficult to control. These delays are mitigated in analog circuitry.

Additionally, for those interested in learning more about analog circuit design, the involved circuitry provides many interesting lessons in signal processing through use of basic circuit components such as op amps, comparators, MOSFETS, logic gates, gate drivers, etc. Creating circuits that interface with a physical audio-generating system fosters a multi-sensory experience that enables a rich and intuitive understanding of the circuit.

3.3.2 Interfacing with the active control circuit

The active control circuit takes in several control voltages (CVs) as control parameters for controlling the pitch of each steel rod as well as the first several harmonics. Digital-to-Analog-Converters (DACs) between a control interface and the active control circuit permit easy and limitless reconfiguration of interface sensor inputs to the sonic outputs. Accepting control voltages also permits easy experimentation with modular synthesizers and other CV output control interfaces (Figure 1).

4. PERFORMANCE INTERFACE

As a starting point for interaction research and control of the instrument, an initial control interface has been prototyped. Deflectable steel tines (steel feeler gauges) are mounted to 3D-printed stands and outfitted with Adafruit MPR121 capacitive touch sensors, QRD1114 infrared reflective proximity sensors, and handmade electromagnetic haptic feedback actuators. The touch of a user's finger is measured via the capacitive touch sensor. The depth of a press is measured by the optical proximity sensor.

The electromagnetic coil located under each tine provides haptic feedback by inducing an alternating magnetic field that vibrates a neodymium magnet attached to the underside of each steel tine. The initial haptic driver has been designed to use the audio signal generated by the vibrating steel rods as the source of force feedback, similar to how a cellist might feel the vibrations from the body of instrument anywhere it makes contact their body. This reestablishes the tangible and bilateral communication that exists between musicians and most acoustic instruments but is missing in most DMIs. This is enabled in part by the analog signal chain on the sound generation half of the system (Figure 2).[1]

5. AN OPEN-SOURCE TOOLKIT

Open source projects such as Arduino[2], Daisy[3], MJbots[4], and the Open Dynamic Robot Initiative [5] serve as models for our open-source toolkit. Similar to these projects, we will provide 3D CAD files, electronic schematics, and code to allow researchers and instrument builders to test their own ideas without the need to invest time and funds into designing from the ground-up. The design of the Hummellaphone consists of off-the-shelf and reclaimed materials and components to provide a flexible and affordable platform for research.

6. PROPOSED STUDIES

Beyond the initial design of the instrument, the Hummellaphone and associated toolkit aims to be a resource for answering our motivating research questions. In this paper we have specifically asked how might the reconfigurability and familiarity of an instrument affect the way musicians explore and adopt a new electromagnetically actuated instrument. We also hypothesize that lower cost and access to open source resources may encourage wider engagement with this emerging area of electromagnetically actuated instruments.

[1] A demonstration video can be found at `https://vimeo.com/798030677`

[2] `https://www.arduino.cc`

[3] `https://www.electro-smith.com/daisy`

[4] `https://mjbots.com`

[5] `https://open-dynamic-robot-initiative.github.io`

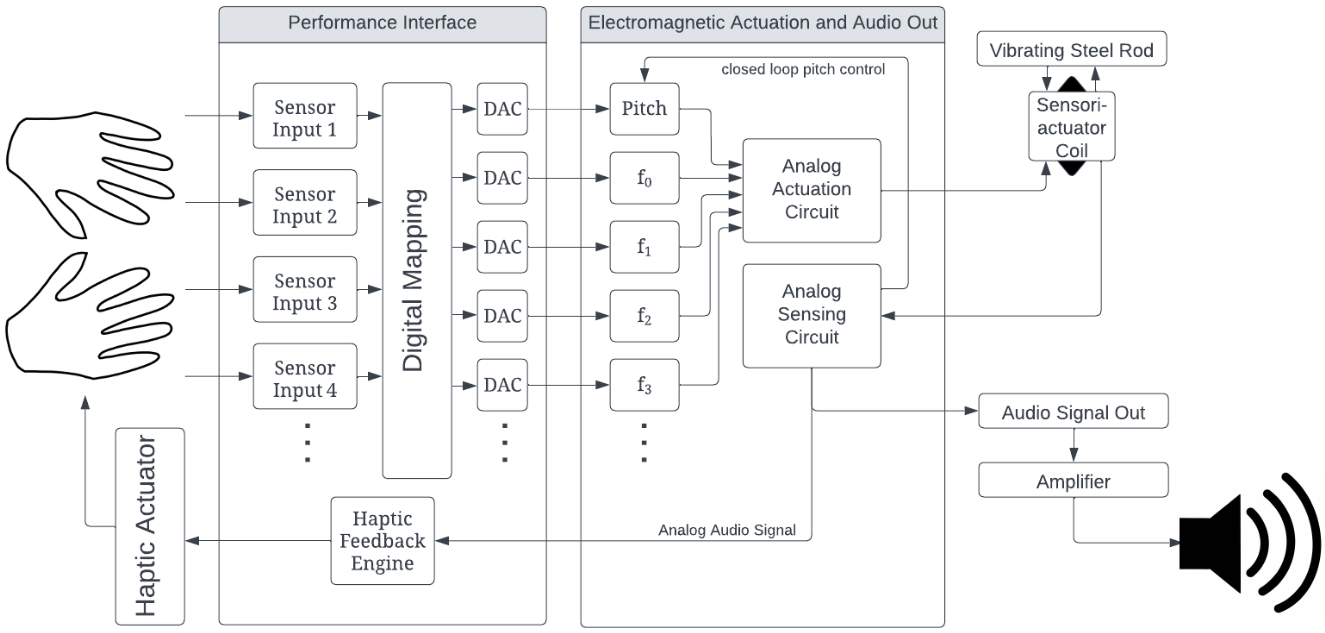

Figure 1: Full System Block Diagram

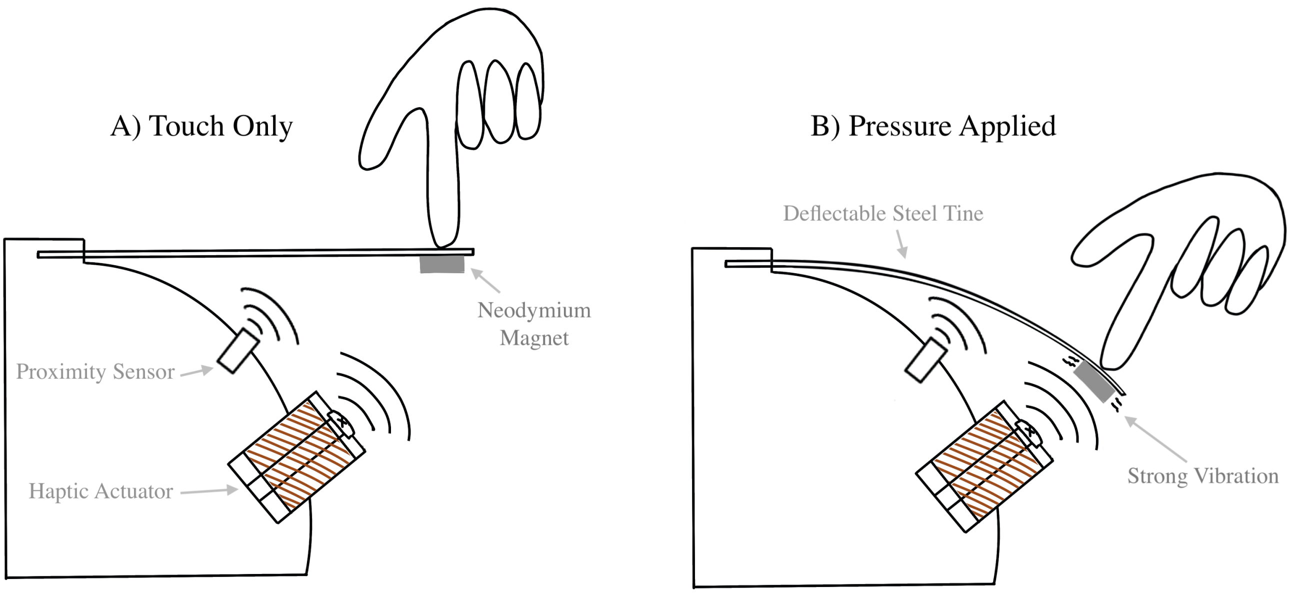

Figure 2: The initial performance interface

6.1 Interaction Design

Although the Hummellaphone wasn't intended to deliberately derive from a keyboard, there are obvious associations with a keyboard instrument: The initial controller is finger-actuated and the sound-generating mechanism is an array of nearly identical tone generators.

Like Harrison et al. [9], we are interested in knowing how modality and morphology of an instrument affect the experience of practicing and performing with it. A series of experiments comparing types of interfaces or several remappings of the same interface might reveal innate preferences in musical interactions. We could study whether people will tend to map their perceptions and expectations of the instrument onto familiar morphologies or interaction modalities, how those are influenced by their prior experiences, and how or whether we can reinforce or disrupt these tendencies.

6.2 Virtual vs Mechanical Sound Generation

The harmonic control and predictable nature of the vibrating steel rods is similar to the additive synthesis of Hammond tonewheel organs. A user study where participants use the same interface to control nearly identical sounds from a physically embodied sound generator or its digital simulation could explore whether physically embodied sound synthesis is experienced differently, and possibly found to be more compelling, even with a decoupled control interface.

6.3 Haptic Interaction

The Hummellaphone's performance interface uses the audio signals generated by the instrument to drive the haptic feedback mechanism. This allows the system to imitate the tactile force feedback felt by musicians playing acoustic instruments, but also provides opportunity to explore other relationships between audio and tactile feedback that would never be possible in a traditional acoustic instrument. For example, one can imagine using haptic force feedback to inform and guide the exploration of the harmonic profile of a sound generating steel rod. In the case of an interface arrangement that resembles the drawbars of a tonewheel organ, force feedback from the interface allows the player to select and tune parameters of the harmonic profile through sense of touch, perhaps isolating force feedback from each harmonic to separate fingers. Would this force feedback promote more sonic exploration when compared to an identical interface with no force feedback? Enabled by the haptic reconfigurability of our system, this is just one of many possible questions that can be explored.

7. FUTURE WORK

7.1 The Toolkit

The project website will host the associated files, designs, and learning modules related to the project. The software for reading sensor inputs and mapping them to the sound generation circuit is designed to be simple and flexible. Custom Arduino libraries will be built to make remapping the interface input parameters standardized and simple. An alternative interface design in progress makes use of reclaimed 3.5" hard drives. Future work will outline the process and craft of creating one-off designs to advocate for and inspire the utilization of limited recycled components.

7.2 Performance Interfaces

Additional interface modules will be developed to encourage and allow rapid reconfiguration of the physical layout and virtual mapping of an interface. Additional sensing methods will be explored, and members of the community will be encouraged to share ideas and designs of their own interfaces. Experiments in utilizing existing DMI controllers and established systems such as modular synthesizers will also be welcome and encouraged.

7.3 Learning Modules & Workshops

Online learning modules that explain the schematics, code, and theory of operation will be provided for makers that wish to understand the science and technology behind an electromagnetically actuated instrument or even build their own. Inspired by projects designed for learning such as John Shive's wave machine [23], a series of modules could follow a similar model where a maker is guided through the process of building their own electromagnetically actuated instrument. Through building and experimenting, the maker gains a deeper understanding of electromagnetics, control theory, analog circuit design, digital signal processing, PCB design, CAD, digital fabrication, etc. Building further on the learning modules, we intend to develop future NIME workshops for exploring rapid prototyping and collaborative creation of electromagnetically actuated instruments.

8. CONCLUSION

This paper has presented the Hummellaphone, a highly reconfigurable, open-source electromechanical instrument. Based on the underlying principles of the Moog guitar, the Hummelaphone sheds deliberate associations with familiar instruments in order to foster experimentation and research within NIME as well as adjacent fields such as haptics, engineering learning, and HCI. Through a low-cost, accessible, flexible, open-source design and online community support, the project aims to lower the barriers to entry, grow interest in, and encourage the development of new electromagnetically actuated sustainer instruments.

9. ACKNOWLEDGMENTS

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10. ETHICAL STANDARDS

This research is conducted in accordance with the NIME Principles & Code of Practice on Ethical Research, and in compliance with the standards and practices of the University of Michigan. The research involved no human or nonhuman animal participants. The authors declare no conflicts of interest. The project aims to minimize its environmental impact through the promotion and use of reclaimed and recycled materials wherever feasible.

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