Design Explorations of Instruments and Interactions with Bidirectional Haptic Couplings

Matthew Davison
Dyson School of Design Engineering
Imperial College London
London, United Kingdom
m.davison23@imperial.ac.uk

Andrew McPherson
Dyson School of Design Engineering
Imperial College London
London, United Kingdom
andrew.mcpherson@imperial.ac.uk

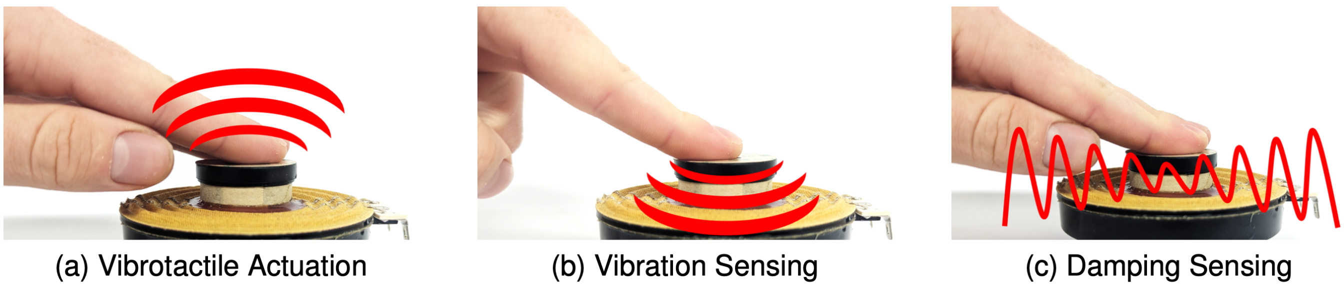

Figure 1: The three main modalities provided by the HaptiCoupler system using a single voice coil transducer: (a) wideband vibrotactile actuation at audio-rate, (b) vibration sensing at audio-rate, and (c) sensing the transducer's mechanical damping

Abstract

Direct interaction with digital synthesisers using audio signals can offer opportunities for intimate and nuanced interaction in digital musical instrument designs. Unlike acoustic instruments, these hybrid instruments tend to follow a unidirectional interaction structure: tactile gestures generate audio signals that are fed into a synthesiser, but there is no vibrotactile feedback from the instrument back to the musician. This paper presents the HaptiCoupler system that enables bidirectional tactile interaction with digital musical instruments using a single voice coil transducer. A study is undertaken with experienced digital musical instrument designers to explore the design implications of introducing closely coupled, collocated haptic feedback in musical systems. The potential creative implications for designers are discussed.

CCS Concepts

• **Applied computing** → **Sound and music computing**; • **Human-centered computing** → **User studies**; **Haptic devices**.

Keywords

Bidirectionality, Haptic Interaction, Vibrotactile, Voice-Coil, Musical Interaction, Hybrid Instruments, Instrument Design

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1 Introduction

The prevalence of screen-based interactions in consumer products and the relative scarcity of tangible interfaces is widely known. The cost and flexibility of generic input/output devices often outweigh the benefits of specialised tangible interfaces for particular tasks. Musical interfaces present a partial exception, since music-specific digital interfaces such as MIDI keyboards, drum trigger pads, and knob or fader-based controls are widely used. The embodied relationship between musician and instrument has been studied [41]; for acoustic instruments, this relationship tends to take the form of a bidirectional, reciprocal coupling where the instrument comes to functionally act as an extension of the player's mind-body, shaping their perception and action [61, 63].

In contrast to acoustic instruments, most digital musical interfaces follow an engineering paradigm of unidirectional control, where data flows from sensors to synthesiser parameters [55] rather than the other way around; such data relationships or mappings have been the subject of considerable study [33, 50]. Within this unidirectional control paradigm, designers sometimes incorporate a return path of vibrotactile feedback, where an output signal from the digital system is fed back to the performer via haptic actuators for the purpose of communicating information on the state of the digital system or simulating the vibrations virtual mechanical-acoustic systems [11, 27]. Such designs will often avoid using tactile input as a sensing mechanism, to prevent coupling between sensing and actuation.

A greater challenge in digital interface design is true bidirectionality, which we define to encompass spatial and temporal collocation of sensing and actuation, which also use the same physical/electrical modality. A bidirectional transducer is a single device that transmits signals in both directions simultaneously, acting as both sensor and actuator. Many electrical transducers naturally work in both directions: a dynamic loudspeaker can be used as a microphone and vice versa, albeit at very low efficiency and capacity in one direction or the other. Designing a transducer that operates efficiently *and simultaneously* in both directions presents a number of engineering challenges, not least around the avoidance of feedback.

In music, the promise of such devices is to enable the kind of reciprocal physical-sonic relationships found in blown reeds, bowed and plucked strings, and many other situations where the instrument is best understood as an assemblage of mechanical and biological systems in a sociocultural context [2]. While advanced force feedback systems provide opportunities to enact such a level of bidirectional couplings in digital instrument designs, these do not always suffice to achieve the type of mechanical and vibrotactile couplings found in musical instruments. The sensor and actuator mechanisms are not well suited to recreation of high frequency vibrations, particularly if stability is to be maintained [49]. This often results in the force feedback being controlled at a contol-rate frequency that is lower that typical audio-rate bandwidths. While sufficient for reproducing low frequency kinaesthetic force, this approach is not usually able to create high bandwidth mechanical couplings. Additionally, the requirement to use a restricted set of tools that support the rendering of haptic forces alongside audio output can limit uptake of such devices [26]. This is in contrast to the bidirectionality within physical domains where mechanical vibrations and acoustic output are naturally mutual entities.

An understudied challenge is around the *use* of such transducers by designers, who may be more familiar with unidirectional control paradigms and where bidirectional transduction may not neatly fit with existing tools and workflows. This paper presents an investigation of these challenges, with a particular focus on the activities of designers. We present the HaptiCoupler, a bidirectional voice coil transducer which simultaneously provides vibrotactile actuation, vibration sensing, and mechanical damping sensing (Figure 1). Rather than being a complete artefact, the HaptiCoupler is intended as a tool for designers to incorporate in their own musical systems. After briefly introducing the HaptiCoupler, the paper presents a design study in which seven participants engaged in open-ended creative explorations over a period of several weeks. We observed a range of creative outcomes where designers created digital resonator instruments (Section 2.1), feedback instruments and other modes of interaction. The study outcomes suggest that bidirectionality results in different interaction techniques compared to typical unidirectional systems, while also showing strategies by which experienced designers negotiate the limitations of technical systems. The paper discusses design implications within and beyond music, including a move from a narrative of *control* to one of *negotiation*.

2 Background

The practice of designing digital musical instruments is one that often involves numerous well established paradigms. These are often appropriated from conventional acoustic/analogue electronic instrument design techniques or wider engineering practices and have a significant effect upon the possible creative outcomes of an instrument. While these paradigms and design patterns are important – they can support faster learning of an unfamiliar instrument and reduce time spent on instrument design in the first place – it is important to acknowledge their influence upon the design process and consider how the process may differ without such paradigms in place.

A unidirectional approach is a design pattern often adhered to within digital musical instrument (DMI) design. This is primarily used as an engineering convenience: adhering to strict input and output definitions enables modularity and separability [42, 50, 74]. The modularity afforded is often seen as a benefit of unidirectional DMI designs, as the control interface can be decoupled from the synthesis process [55]. Likewise, each individual element of the signal chain, including audio effect modules, can be interchangeable at will. However, as Cook [15] states, different creative outcomes will likely be achieved when the controller and synthesiser are decoupled entities rather than part of a tightly coupled homogenous system. Furthermore, this decoupled approach can contribute to a loss of intimacy between the musician and the instrument system.

This prevailing unidirectionality creates limited feedback paths from the instrument system back to the musician. Feedback often relies heavily upon auditory and visual elements, while the input modality is primarily tactile and kinaesthetic. Unidirectional paradigms often also prevail due to the complexities of implementing bidirectionality. The technical systems upon which DMIs are built encourage a unidirectional approach, i.e. systems have separate sensors and actuators for input and output [50]. In cases where haptic feedback is provided in a design, it is sometimes intended to simulate mechanical systems at sub-audio bandwidth, or might convey a form of higher level symbolic or semantic information.

2.1 Digital Resonator Instruments

We use the term *digital resonator instrument* (DRI) to signify a class of digital instruments where a numerical model of a resonant system such as a string, plate or air column is excited by a continuous audio signal. In contrast to symbolic systems such as MIDI controllers, DRIs promise to offer a more direct interaction with synthesis models [59]. DRIs typically involve an audio-rate sensor (such as a piezoelectric pickup, accelerometer, or microphone) that produces an AC signal in the audio frequency range. This signal is fed directly into a digital resonator, examples of which include physical modelling synthesis [54, 70], simple Karplus-Strong string models [35, 38], or physically-informed models that do not directly model the physical behaviour of any specific system [14]. When sensor data is fed into the digital resonator at audio-rate, it excites the resonant model and produces an audio output. The lack of any feature extraction (sensor data is injected as an audio signal) enables varied and nuanced gestures to be used to create differing timbral outcomes. For instance, when using a surface with a piezoelectric pickup mounted to it, tapping the surface will sound different to scratching it. Using a physical model of a metal plate as an example, it is likely that the tapping excitation signal will produce an audio output that sounds similar to tapping a physical plate, and the scratching excitation producing an output similar to scratching a physical plate. The system does not require knowledge of what 'tapping' or 'scratching' sounds like, and no classification or detection algorithms are required. Physical interfaces for DRIs are usually designed to impart as little acoustic resonance or timbre influence as possible on the input signal, so that these qualities can be determined by the digital model. This is often achieved through using a damped surface or damped string to reduce physical resonant modes [35, 54].

Although the richness of the audio-rate coupling appears to be a benefit compared to reductive symbolic representations, especially for expert instrumentalists [36], the action-sound link remains unidirectional. Energy is introduced into the system by the musician, but energy is not returned to the musician in the tactile domain. This situation is shown in the diagram in Figure 2. Though many DRI designs include passive tangible elements that mimic acoustic instruments (such as muted guitar strings or drum heads), nothing about the tactile response of the instrument changes because of what happens in the digital domain. As such, they do not fully model the tactile, dynamic coupling of musician and acoustic instrument [35].

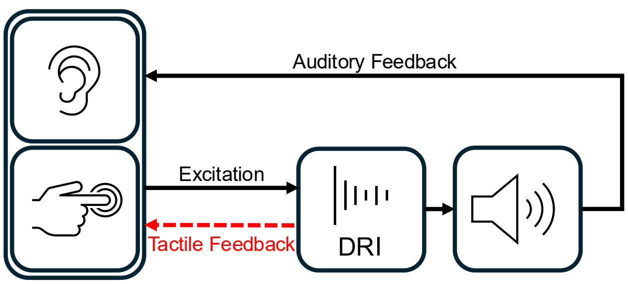

Figure 2: The conventional method of interacting with a DRI: tactile input is picked up by a sensor and fed into the resonant synthesis model as an excitation input. The output of the resonant synthesis provides auditory feedback however the tactile feedback link is missing.

2.2 Force Feedback in DMI Design

Haptic couplings are an important part of instrument designs – providing bidirectional flow of energy between the musician and the instrument [63]. While many instruments provide such couplings intrinsically in their design, couplings can also be achieved with digital instruments using haptic feedback. To create a rich, closely coupled experience, sensing and haptic actuation should occur simultaneously, in the same modality, and be collocated [73]. Research into haptic feedback for digital musical instrument design has taken place over numerous decades. Though other forms of haptic feedback have also been investigated, two main forms of haptic feedback have been researched more extensively for DMI design: force feedback and vibrotactile feedback [7]. An overview of these two types of haptic feedback can be found in [32].

Previous academic endeavours into creative close couplings that link the musician with the digital instrument in the haptic domain have focused upon force feedback haptic modalities where bidirectionality is achieved through coupled sensing and actuating to create the illusion of objects or forces. Within force feedback device research, most force feedback haptic systems fall into one of two broad categories: impedance and its dual, admittance [39]. Both approaches use the power conjugates of force and velocity to sense and actuate. Impedance-based designs sense a velocity or displacement and actuate a force based upon this input. Admittance-based designs operate in the opposite manner, sensing a force input and actuating a velocity or displacement. Similarly to electrical impedances involving voltages and currents, only one of these can be independently controlled (e.g. as a voltage or current source in the electrical domain) while the other is determined by the impedance or admittance of the system[32]. Due to the opposite sensing and actuating methodologies, admittance control tends to perform better at rendering stiff virtual surfaces whereas impedance control is better suited for rendering low inertia [1]. In both cases, the perceived bidirectionality of interaction is formed by the control loop between sensing and actuating, modelling either the impedance or admittance of a virtual environment to respond to user input.

Within DMI design, force feedback was initially explored by Cadoz using the CORDIS-ANIMA system [12]. This system provided a complete solution for haptic interaction with physical models - performing both the physical modelling synthesis and force feedback interaction. Subsequent notable force feedback designs for musical interaction have included the Plank [78] and the Firefader [4], both of which offer a single degree of freedom. Force feedback provides an intuitive link with physical modelling synthesis techniques - interaction devices are able to exert a force upon the user that is directly derived from the physical model at the simulated point of contact; sensing mechanisms provide a displacement or velocity reading to return into the physical model. While advanced force feedback devices, when paired with an effective physical modelling algorithm, can provide realistic kinaesthetic feedback to the musician, there exists a level of separation between the haptic force feedback and the audio output of a system. Usually the haptic feedback uses a lower sample rate than the audio output, operating at a 'control rate' that is often around 1kHz [25]. This separation of domains compels a conscious decision from the designer as to what feedback should be present in each domain – a point of separation between haptic and audio must be enforced and designed.

Devices that provide force feedback haptics, such as a robot arm operating with impedance control, are not typically well suited recreating high frequency vibrotactile feedback [48]. Previous research has also examined the combination of force feedback haptics with vibrotactile, audio-rate haptic feedback [48, 82]. This enables the same bidirectional interaction afforded by other force feedback systems, while also enabling additional vibrotactile feedback at audio sample rates.

There has been prolonged interest in force feedback haptics for several decades yet these technologies have become less widespread in DMI design than might have been expected [79]. While the often prohibitive expense of force feedback haptic devices certainly has limited uptake of the technology, another major factor is the toolchains and systems required for cohesive audio and haptic design [26]. Such systems - often built on a physical modelling framework - can enable design of the synthesised audio output and force feedback control system [5]. Force feedback designs, therefore, are restricted to use with tools and systems that are compatible with the haptic hardware. With continuously evolving device support and standard for device communication in computer systems, this can pose an additional challenge for the longevity of any force feedback instrument systems [26].

2.3 Vibrotactile Feedback in DMI Design

While there are many existing examples of vibrotactile haptic feedback in DMI designs, these tend to operate with decoupled sensing and actuation – the sensing modality is separate from the vibrotactile actuation. There are also two main techniques for deriving haptic signals: synthesis driven or symbolic haptic signals. Vibrotactile feedback that is synthesis driven creates a vibrotactile signal that is directly derived (possibly with additional processing applied) from the audio output of the digital synthesis. This technique often tries to mimic the vibrations found in acoustic instruments, where the audible sound produced and mechanical vibrations are inherently linked [47]. Symbolic haptics, on the other hand, provide vibrotactile feedback that is representative of a more abstract parameter of the synthesis system. This could be pitch and tuning [34] or other audio effect parameters such as the low frequency oscillator for a tremolo effect [68].

Closely-coupled vibrotactile interaction with DRIs is usually avoided due to the issue of feedback. As Christensen et al. write [13], their approach of using a piezo as a vibration sensor for an input to an DRI while actuating the same surface with a voice coil transducer meant that "vibrations of the disk were picked up by the piezo resulting in a feedback loop". After trying feedback suppression algorithms, they ended up mounting the sensor and actuator on separate (and mechanically decoupled) surfaces. Likewise, when discussing their digital resonator instrument 'the Tickle', Neupert and Wegener [60] state that "Haptic feedback is challenging to implement due to the feedback into the sensor, but can give the user a much more intense sense of reality." Additionally, Piepenbrink [66] found that low frequency feedback could occur between the embedded loudspeaker and the accelerometer in their digital shaker. This was mitigated using a high pass filter though it was also noted that this feedback could be a possible extended performance technique.

While it is challenging to implement closely coupled vibrotactile interaction due to feedback, certain DMI designs (or interfaces created for interacting with sound synthesis methods) have approached a closely-coupled vibrotactile haptic experience. Generally, this is achieved through sensing and actuation in different modalities, to avoid interference or feedback between sensing and actuation. If these modalities are perceptually similar, an experience that is approaching closely coupled can be achieved. Papetti et al. [64], for example, use a load cell to measure downwards force and a Haptuator mk. II haptic actuator to exert vibrotactile feedback.

2.4 Feedback Instruments

While unstable feedback between sensor and actuator is undesirable in DRIs, it can also be used as a sound creation method in other forms of DMI. Feedback between vibrotactile actuators and sensing transducers is used as a sound creation technique in self-resonating feedback instruments. Feedback instruments often utilise the coupling between a vibration transducer, or loudspeaker, and a pickup to create self-sustaining feedback [9, 22, 40]. A combination of mechanical resonance coupling and digital signal processing can change the timbre, while tactile interaction with the assemblages can affect timbre or feedback levels. This interaction is also noteworthy when considering tactile bidirectionality. Although there still exists a separation between output (actuator) and input (sensor) of the system, the mechanical coupling between them is less clear cut. Interacting with this is therefore a bidirectional process – at any single touch point a person is able to both exert energy upon the feedback system (by tapping, hitting, shaking, etc.) while simultaneously receiving vibrotactile energy from the resonating body.

2.5 Self-Sensing Actuation for Close Couplings

To achieve a closely-coupled interaction – where sensing and actuation are simultaneous, collocated and in the same modality - while mitigating the issue of feedback between actuation and sensing, self-sensing techniques can be employed. This is where the same transducer is used as a sensor and actuator simultaneously [31]. Self-sensing techniques have previously been used in haptic interaction devices. Along with simplifying feedback cancellation, self-sensing techniques can reduce component counts - potentially reducing complexity, cost, and physical size. Dementyev et al. [19] used a linear resonant actuator and back-EMF measurements to determine the damping applied to the actuator. In subsequent work [18], they use current sensing to support simultaneous sensing and actuation. Manabe and Fukumoto [45] sense finger taps upon the outside of in-ear headphones by measuring the current through the loudspeaker's voice coil. Youn et al. [83] use microspeakers with hydraulics to create button-like haptic interfaces – actuating vibrations with the speaker and sensing user presses by measuring the change in inductance of the speaker. Within DMI design literature, the authors of this paper have previously used a self-sensing vibrotactile transducer for interaction with physical modelling synthesis [16]. The work used the same modality for both sensing and actuating – using similar voltage-current separation techniques seen in other haptic feedback research [18, 19, 29, 69].

When using audio-rate signals for sensing and actuation, self-sensing techniques can also mitigate the issue of feedback with the addition of vibrotactile feedback to DRIs - as described in Section 2.3. With separate sensor and actuator devices, actuated mechanical vibrations from the output of the DRI are sensed by the vibration sensor and fed back into the DRI, potentially creating unstable oscillations. The feedback must be mitigated for interaction with DRIs to ensure stability and maintain the timbral qualities of the digital resonator. Using self-sensing techniques, the feedback occurs purely in the electrical domain, which is easier to cancel using a model of the voice coil's voltage-current transfer function (rather than requiring modelling of the complex mechanical propagation between a separate actuator and sensor). This simplified actuation-sensing transfer function through self-sensing has previously been exploited in active mechanical and acoustic control literature –

where self-sensing actuators (both voice coil and piezoelectric) have been used [23, 24, 44].

3 Technology: the HaptiCoupler

The study presented in this paper uses the HaptiCoupler system created by the authors, the design of which is summarised here but is not the main focus of this paper. This system enables bidirectional tactile interaction using a single voice coil transducer. Vibrations can be both sensed and actuated at audio-rate (44.1kHz). This allows a person to excite a synthesis model through tactile input, while feeling the vibrations from the audio output of the model simultaneously at the same point of contact. The system enables closely-coupled interactions as described by Strohmeier et al. [73]: sensing and actuation should be simultaneous, collocated, and in the same modality. Unlike closely-coupled force feedback approaches, the HaptiCoupler system does not require the use of particular synthesis frameworks with inbuilt haptic rendering algorithms. Instead, the audio output of the synthesiser is used to directly drive haptic vibrations. Additionally, instead of utilising separate sensing and actuation techniques to control the mechanical conjugate variables of velocity and force, the bidirectionality of the HaptiCoupler operates at a component level. The same voice coil is used for both sensing and actuating, using the electrical conjugate variables of voltage and current for actuating and sensing, respectively.

3.1 Self-Sensing Operation

The issue of unstable feedback is mitigated using a self-sensing actuator configuration. The HaptiCoupler system uses a similar approach to the previously described self-sensing methods in existing literature: actuating with a voltage signal and sensing with current [18, 45, 83]. The amplified haptic actuation signal is delivered to the voice coil transducer as a voltage, causing it to vibrate; this is the same principle as an audio amplifier and loudspeaker. These vibrations can be felt by the user. Meanwhile, the current through the transducer is measured at audio-rate and used for vibration sensing (effectively producing a tactile contact microphone), with further feature extraction performed for measurement of mechanical damping.

Previous methods of self-sensing for haptic feedback applications have often used linear resonant actuators (LRAs) [71], which offer high efficiency in a small form factor when driven at their resonant frequency, but are much less efficient when driven at any other frequency, restricting their usable frequency range. Though limited in bandwidth, the resonant frequency can be modulated by a low frequency envelope to create haptic effects. This trade-off makes them well suited to mobile applications and basic haptic feedback situations where notifications or simple effects such as virtual 'clicks' are required. For richer haptic experiences, however, a wider frequency range of actuation is needed [80]. The system created for this study uses voice coil surface exciters, which are effectively cone-less loudspeakers that can operate over a wide audio band.

3.2 Sensing Modalities

Besides its role as an actuator, the HaptiCoupler offers two sensing modalities: tactile vibrations and mechanical damping. Vibrations are sensed in the same manner as a dynamic microphone: movement of the voice coil relative to a permanent magnet induces a current in the coil. This current, which is proportional to the velocity of the coil relative to the magnet, can be measured, digitised and used as an audio-rate excitation signal.

If the transducer were not also used for actuation, measuring the current would already be sufficient to generate an excitation signal for a DRI. Simultaneous actuation, however, introduces the possibility of feedback between the actuation and sensing modalities. Feedback is suppressed by estimating the current due to the actuation voltage and subtracting this estimate from the measured current. Given a perfect estimate, the remaining current signal would be entirely due to external vibrations induced by the musician. In reality, the cancellation process is not perfect, but it substantially reduces the loop gain before the system goes into self-oscillation.

The current induced by the actuation voltage can be estimated using the electrical impedance of the transducer. Using a model for the transducer's impedance, the current can be estimated using $I = \frac{V}{Z}$ where Z is the complex impedance of the transducer. The impedance of the voice coil transducer used in the study (Dayton Audio EX32VBDS-4) is shown in Figure 3. Voice coil transducers exhibit a mechanical resonance due to the compliance and moving mass of the system. This resonance creates a peak in impedance, shown in Figure 3 at 100Hz. A rise in impedance at high frequencies is caused by the electrical inductance of the voice coil.

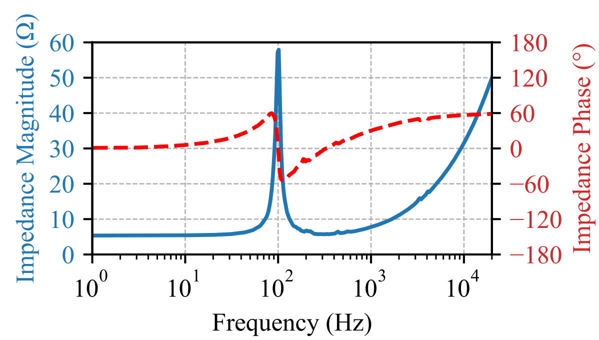

Figure 3: The magnitude (continuous blue line) and phase (dotted red line) of a Dayton Audio EX32VBDS-4 voice-coil transducer's electrical impedance, measured using a Dayton Audio Test System V3.

The system is also able to detect changes in mechanical damping of the system, such as when the musician rests a finger on the top of the transducer. This change is detected by actuating with a low-amplitude voltage at the resonant frequency of the transducer, while measuring the amplitude of the current that comes back. When the mechanical damping increases (by touching the voice coil with a fingertip, for instance), the peak in impedance at the resonant frequency reduces. This can be seen in Figure 4, showing the magnitude of the electrical impedance around the resonant frequency in undamped and damped states. When the mechanical damping increases, the current at the resonant frequency will also increase. The damping parameter measurement is isolated from any broadband haptic actuation signals using the Goertzel algorithm [28].

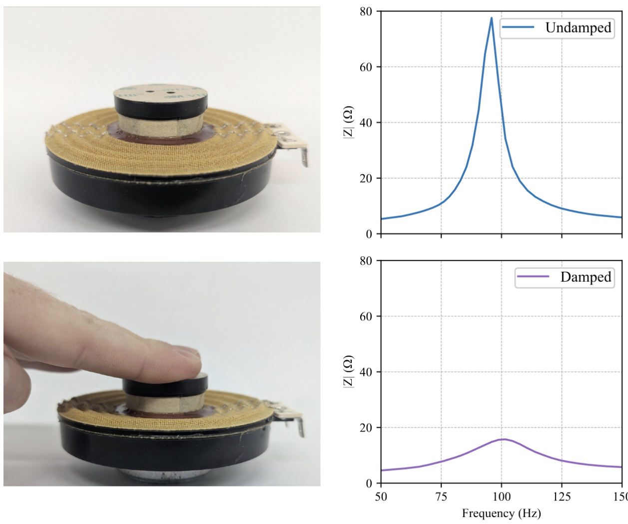

Figure 4: The electrical impedance of the voice coil transducer around the resonant frequency in mechanically undamped and damped conditions.

3.3 System Implementation

The HaptiCoupler system uses a Teensy 4.0 microcontroller board with a custom printed circuit board (PCB). The PCB has a class-D audio amplifier (Analog Devices MAX98389) which includes audio-rate current sensing. The Teensy 4.0 functions as a USB audio interface and signal processor. While the implementation details are not the main focus of this paper, the kit is fully open source and further details are available in the project's GitHub repository[1]. This includes schematics, PCB layout, firmware, and 3D printing design files alongside usage documentation.

Actuation signals can be routed from a host computer to the Teensy, which then processes the signal and routes it to the amplifier. The Teensy processes the sensed current signal from the amplifier, as described in the previous section, to cancel feedback and estimate damping. The excitation signal (current signal with feedback cancelled) is sent as a USB audio signal to the host computer. The damping parameter is sent to the host computer via USB MIDI. Signal processing parameters can be adjusted by the user using USB serial and a web-based interface.

The use of USB audio rather than analog I/O was chosen as a design simplification for the study: participants are able to integrate the device into digital processing workflows using only their computer and no other hardware (such as audio interfaces). However, a significant drawback of USB audio was that the round-trip latency was approximately 35ms. This is higher than ideal for musical interaction [51, 81], but we consider it low enough to be usable as an interface. Other alternatives, for instance, using an embedded system designed for audio synthesis such as Bela [52], would enable a lower latency to be achieved. In doing so, however, participants are restricted to sound synthesis options that are available within the particular embedded ecosystem. Furthermore, the recruitment of participants would be restricted to participants familiar with that system. Given this, we decided to accept the limitation of additional latency for the further creative freedom that a USB audio connection facilitates. We discuss the effect of this design constraint on our participants in Section 5.4. While USB audio connections were provided as a default for ease of use, the open source firmware was also provided to the participants. This enabled the possibility of developing systems where the audio processing was performed directly within the Teensy itself.

[1]https://github.com/davisonaudio/HapticInstrumentWorkshop

4 Study Design

The design study involved experienced DMI designers exploring possible creative uses of the HaptiCoupler system. Through discussing their design outcomes and interactions with their resulting designs, the study aimed to explore the following ideas:

- Does the shift from conventional unidirectional methods of interaction towards bidirectional tactile interaction cause a significant difference in the design outcomes?
- Do methods of interacting with interfaces seem to differ between unidirectional and bidirectional interfaces?

Each participant received a kit containing the Teensy 4.0 microcontroller and HaptiCoupler amplifier PCB, a Dayton Audio EX32VBDS-4 voice coil transducer in a 3D-printed enclosure, a USB A to micro-USB cable, a 9V DC power supply, and two additional screw on caps for the transducer. An example kit can be seen in Figure 5.

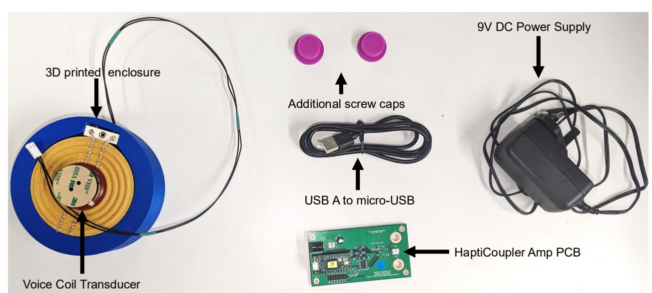

Figure 5: The study kit given to each participant.

Participants were contacted via recruitment emails sent to academics and practitioners, many of whom disseminated the call for participants to their students and collaborators. Participants were required to have previous experience in DMI design, synthesis design, or interaction design for music technology. This experience could be in software, hardware, or cross-disciplinary. After interested parties were recruited for the study, each participant was introduced to the system in an initial 30 minute introduction either in person or by video call. Details of the basic functions and usage of the kit were explained in these sessions. A short online survey was then sent out to record each participant's musical and engineering background along with their initial ideas for exploration with the kit. Each participant was given a minimum of three weeks with the kit to explore creative possibilities.

Following the exploration period, participants were invited back for a wrap up session, lasting approximately one hour. During this session, a semi-structured interview was conducted to explore the participant's experience with the system and the creative outcomes produced during the study. The details of this study were approved by the research ethics board of the authors' institution.

We considered an alternative methodology involving a short workshop-format study in which participants could explore the interface for a brief time in a controlled environment. We decided that a longer-form study in the participants' own working environments, even with fewer participants, was likely to yield deeper insights into the design implications of bidirectional tactile interaction. Allowing several weeks of exploration allowed the participants to become familiar with the system and, more significantly, integrate it into their own creative and design practices. Longer-form explorations also allow time for refinement through iteration [62]; these ideas are also expressed in the idea of "curated research" [10]. Moreover, haptic feedback is a technology that many interface designers do not have prior experience with [56]. By allowing a longer period of time for exploration, we hoped that previously inexperienced designers would have sufficient time to explore the possibilities of vibrotactile feedback.

5 Study Outcomes

Ten people responded to our call for participants and were given HaptiCoupler kits, of which seven participants completed the study in the allotted time frame. Three did not complete the study due to time constraints or technical difficulties with the kit. The participants who completed the study ranged in age from 24 to 46 and all identified as male. All of them had a minimum of three years of design or engineering experience for audio/music-based systems. Further information about each participant is shown in Table 1. The information in the table was gathered from the participants using an initial online survey sent after the introductory session. Participants had the option to either remain anonymous or be identified in research output from the study.

5.1 Overview of Outcomes

Participants generally focused either on development of additional hardware elements or on developing novel synthesis ideas. Following the conclusion of the study, an inductive thematic analysis was performed on the transcribed text from the concluding study sessions. Transcripts were coded and grouped into themes that are explored further below. The outcomes of the study can be categorised into three broad categories:

(1) Interactions with DRIs, where the HaptiCoupler provides an excitation signal to a physical modelling synthesiser (or other form of resonant synthesis) and the output of the synthesiser is used as both an audio and haptic excitation output.
(2) Feedback instruments – where the coupling between mechanical, acoustic, sensing, actuating, and digital domain produces sustained feedback that can be altered through both tactile interaction and digital processing.
(3) Interfaces with symbolic haptic interaction, where some form of feature extraction is performed upon the excitation input to produce symbolic information (such as hit detection). Haptic actuation may be representative of synthesis parameter values, rather than audio output signals.

These categories provide a coarse taxonomy of the study outcomes; however, the boundaries between categories often become blurred. With a high enough actuation signal level, for instance, a DRI can start to produce self-sustaining oscillations, becoming a feedback instrument.

Participants also drew upon their own musical practices that are shown in Table 1. Those with a background situated more in experimental noise music tended to produce more experimental and abstract creative outcomes. All participants produced outcomes that were similar to their initial ideas shown in Table 1, though some added adaptations based upon the constraints and affordances of the HaptiCoupler system. Some of the participant's outcomes can be seen in Figure 6. Each participant's outcomes are detailed further below, with participants labelled from Clemens to P6.

P1 (Clemens Wegener) added a physical surface to the top of the transducer and paired it with CHAIR Audio's EXC!TE Cymbal Pro plugin[2], creating a DRI. The hardware additions consisted of a large medium-density fibreboard (MDF) rectangular top, MDF sides to ensure stability, and a foam base underneath the transducer to decouple the vibrations from the table surface. A side-on photo of this system is shown in Figure 6(a) and an annotated cross sectional diagram of this system is seen in Figure 6(b). Clemens experimented with thin aluminium sheet but found that the metal was not rigid enough - the vibrations would not propagate out across the entire surface. After trying a thicker MDF sheet, he settled on a thin MDF sheet, concluding that a suitable material should be "something very stiff and very light".

While initially using the foam underneath the transducer to decouple the system from the table and maximise the vibrations transferred to the interaction surface, Clemens also discovered that it was "nice to have some travel when you when you push on it". It was noted by Clemens that the interaction with the extra downwards travel due the foam felt like a combination of a drum membrane and electronic instruments "where you have a damping sensor, or after touch" that is less familiar in acoustic instruments. The vibration sensing signal was sent to the excitation input of the cymbal modelling plugin (the plugin supports audio signals as a resonant excitation modality) and the damping parameter from the HaptiCoupler was mapped to the damping control on the plugin, that controls the decay of the cymbal resonance. Clemens noted that, although the mapping of the damping parameter didn't work in all circumstances (due to the crosstalk from the actuation signal), the parameter was "super intuitive to incorporate" when mapped to the corresponding damping parameter, enabling the "perfectly natural" interaction to "excite the resonance and also dampen it afterwards".

[2]https://www.chair.audio/product/excte-cymbal-pro/

Name	Years in Engineering or Design	Engineering & Design Experience	Musical Background	Instruments played	Initial Idea(s)
Clemens (P1)	6 - 10	Building prototypes for acoustic excitation.	Performs electronic music and interested in acoustic sound. Background in electronic music production and performance and designing electronic instruments.	Piano, MIDI Controllers, Computer.	Drum-like interaction and inharmonic timbres due to the mountability of a two dimensional plate.
Eoghan (P2)	3 - 5	Granular synth in Max/MSP with a custom controller (Arduino and custom MDF enclosure), 3D printing.	Experimental improvisation, Irish traditional music, Punk and rock music, Noise.	Banjo, electric guitar, bass VI, analogue synthesizers, DIY granular synth and controller.	Exciting various physical models. Designing and printing custom attachments for percussive interaction.
Abhiram (P3)	3 - 5	Slide-string instrument DMI with wood & 3D printed elements,piezo sensor and a load cell along with a Bela.	Carnatic music, Country/blues/rock/Hawaiian (slide guitar).	Carnatic classical singing, piano, and guitar (beginner).	Try with slide-string synthesis plugin and also with other plugins like Modus from Physical Audio.
Dimitris (P4)	6 - 10	Designed live coding instrument with custom DSL embedded in Haskell, a programmable keyboard, and MIDI controllers.	Free-form experimental electronics, algorithmic composition, Jazz and Prog-inspired fusion, IDM-style dance music etc.	Piano, guitar, bass guitar, saxophone, synthesizers, live coding, & misc electronics	(1) Interact with physical models of percussive instruments and surfaces, with some degree of realism both in the sound design and their interaction. (2) Using it as a physical mediator of arbitrary feedback synthesis systems, where one can both excite and dampen the loop, potentially involving other instruments too. (3) Using it not for audio but for “control voltage" tactile sensing and interaction.
Miguel (P5)	11 - 20	Electronics, DSP, circuit bending. Creates augmented, hyper, and biosignal-driven instruments	Aggressive noisy experimental NIME music - creates and performs on self-built and traditional instruments	Guitar, cello, custom made experimental electronic instruments	Feedback loops using an acoustic cello as the actuator and physical models to explore unstable textures and breaking points of all components.
P6	6 - 10	Designing patches with Max/MSP, Ableton, Max4Live, Tidal Cycles. Produced drum machine with button lights and knobs using the Electro-Smith Daisy	Noise, ambient, music concrete, performance art. Makes textural ambient / noise music, largely based on sample manipulation and effects chains with feedback	Computer. Previous experience of clarinet, piano and bass guitar.	Mapping the single damping interaction to many parameters at the same time in non-linear, interpolated manner, such as: - Different effects parameters - Feedback amount - Other parameters that seem relevant while exploring
Levin (P7)	3 - 5	Designing with Bela, C++, Inkscape, Fusion360. Created acoustic-digital hybrid instrument with real string to excite two virtual strings modelled using finite differences	Playing: jazz, pop, neo-soul, rock. Design: usually more experimental	Guitar and piano	Active control of an acoustic guitar: changing the vibrational characteristics of the guitar to achieve interesting timbres while keeping the playability of the acoustic guitar - the DSP might involve filters, dynamic RMS level-tracking, audio effects

Table 1: Background information of each of the study participants

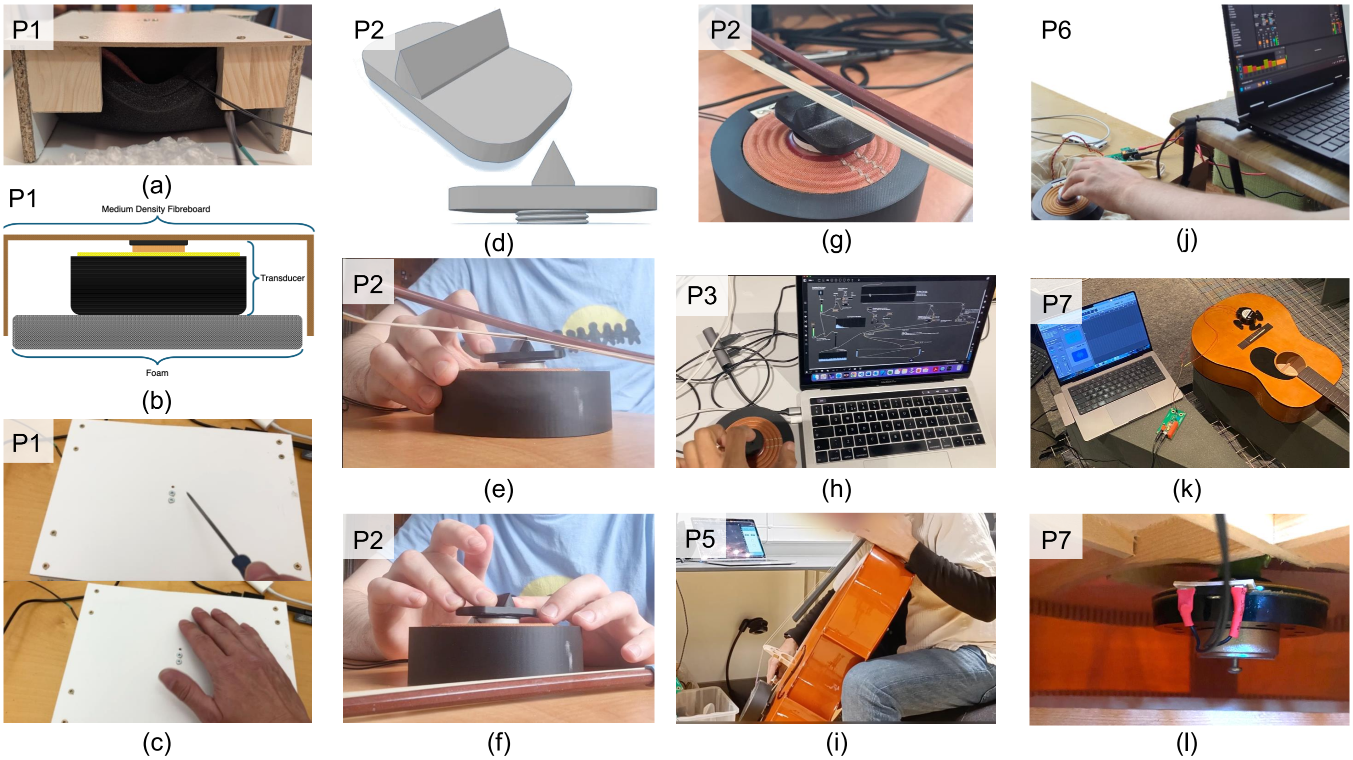

Figure 6: A variety of the study outcomes from the participants. Subfigures (a) to (c) show the surface enclosure created by Clemens and interaction through tapping with a screwdriver and resting palms on the surface. Subfigures (d) to (g) show Eoghan's addition of a 3D-printed top and subsequent bowing and tapping interactions. Subfigure (h) shows Abhiram's interaction with the Max/MSP string model, (i) shows Miguel's setup with the voice coil mounted to the body of a cello, and (j) shows P6's interaction with parameter mappings in Ableton Live. Subfigures (k) and (l) show Levin's experiment setups, first with a voice coil on the top of an acoustic guitar to perform initial measurements in (k), then with a voice coil mounted within the body of an acoustic guitar in (l).

P2 (Eoghan Ó Néill) used the HaptiCoupler system in conjunction with Physical Audio's MODUS[3] audio effect plugin. This provides a physical model of two non-linear metal plates with an inter-coupling element, simulated using modal synthesis [21]. After expressing the desire to use a violin bow, Eoghan then designed a 3D-printed plastic attachment for the transducer, designed to facilitate both finger tapping and bowing interactions. A rendering of this attachment design can be seen in Figure 6(d). A photo of Eoghan interacting with the system using a violin bow and pressing on the voice coil is shown in Figure 6(e). Tapping interactions are shown in Figure 6(f). Eoghan explored sounds that could be considered somewhere between DRI usage and feedback instrument by pushing the actuation level high enough to achieve self-sustained feedback. The system maintained stability until the voice coil was dampened, at which point the system could go unstable and produced self-oscillations. Eoghan used finger tapping, pressing on the voice coil, and bowing on the voice coil. He described the vibrotactile feedback to have "affected the way that the bow stuck and slipped from the bowing attachment" and that pressing on the voice coil created "distortion which fed back into the feedback cycle". The transducer was placed upon a desk, which led to an audible output from the transducer through the coupling to the desk surface.

P3 (Abhiram Bhanuprakash) explored the HaptiCoupler system with a self-developed physical model of a virtual string, avoiding hardware additions to the system. A photo of the interaction with this physical model in Max/MSP is shown in Figure 6(h). The string synthesiser models the sound of a slide guitar instrument and audio signals can be used to excite the modelled string. The existing controller interface that Abhiram has designed for the synthesiser uses piezoeletric sensors coupled against real guitar strings that are muted (to minimise the resonance of the physical strings themselves). Abhiram explained that their interest in using the HaptiCoupler system was that without haptic feedback from the controller's strings "you don't feel it's alive". While the interaction modalities afforded by a voice coil differ from that of a guitar string, Abhiram stated a wish to explore coupling tactile sensing and actuation solutions using tapping and hitting paradigms with the HaptiCoupler, intending to then explore similar possibilities applied to string actuation.

[3]https://physicalaudio.co.uk/products/modus/

P4 (Dimitris Kyriakoudis) explored several ideas. This included ideas of symbolic haptic feedback – where the level of haptic feedback indicates the level of a modular synthesiser's control voltage (CV) signal. This was used alongside the damping parameter, where an increase in damping on the transducer's surface could 'compress' the CV signal, providing tactile dynamic range control. Dimitris stated that with more time, extraction of high level features (such as tapping or pushing on the transducer) would have been the next steps, integrating it into a live coding setup. Additionally, they explored the creation of feedback instrument systems using Pure Data (PD) and modulating the parameters of an FM synthesiser using a low-pass filtered audio signal from the transducer.

Instead of direct tactile interaction with the transducer, P5 (Miguel Ortiz) mounted the transducer to the body of a cello. This coupling was used in conjunction with various sound processing techniques, including a physical modelling plugin and convolution with warped impulse responses of another cello body. The audio signal from the HaptiCoupler was routed through the signal processing and back out of the computer to the HaptiCoupler for actuation. This formed a feedback instrument system that could be interacted with using different fingerings on the strings, holding the cello body in different places, and changing the mounting position of the transducer. The participant described interaction as "surfing" the edge of self-oscillation and feedback rather than the traditional idea of "control". Miguel mentioned inspirations from Melbye's feedback-actuated augmented bass – a feedback instrument that uses magnetic pickups and a loudspeaker embedded in a double bass instrument [53]. The participant expressed a desire to use the HaptiCoupler system, with its single point of contact for sensing and actuation, to get more of the "colour" of the instrument's body, rather than use a loudspeaker which can sound "too clean".

P6 decided to focus on the damping parameter control - using this to map to multiple parameters in an Ableton Live system. Using the "Max4Live Essentials Multimap", the single MIDI parameter control was mapped to various effects parameters while playing an audio sample – such as playback speed, distortion, and equalisation values. The mappings could be non-linear and several set 'states' could be defined at certain input values, with interpolation between states. The output of Ableton Live was sent to the transducer and to headphones. The audio-rate excitation input was not used. Through the addition of haptic feedback, P6 stated that the system felt more "alive". The haptic feedback also had a notable side effect of adding noise to the damping parameter value; strong haptic transients from the output signal would cause the damping value to jump and oscillate briefly, adding some unpredictability to the system through this effective feedback loop.

P7 (Levin Schnabel) used the HaptiCoupler system for the active control of resonant modes of an acoustic guitar. This involved the implementation of techniques discussed by Berdahl [3] to alter the decay times of particular resonant modes. For effective active control, Berdahl emphasises the importance of collocated sensing and actuation – which Levin felt would mean that the HaptiCoupler is well-suited to this application due to its inherent collocation. To achieve such control, low latency between sensing and actuation is necessary, precluding the use of the provided USB audio connection. Instead, Levin opted to modify the HaptiCoupler firmware directly - implementing the required filtering directly on the Teensy 4.0. While initially also aiming to sense and control the vibrations of the strings as well as the body, Levin found after initial experimentations that the current feedback from the voice coil was not able to pick up the vibration of the strings directly.

Focusing on control and damping of resonant modes within the instrument body, Levin implemented a bandpass filter within the system firmware between the current sensing signal and the actuation signal, using the approach described by Berdahl et. al. [6]. After experimentation with actuator placement upon the guitar's soundboard to find resonant modes, Levin performed tests of the resonant damping performance using an impact hammer striking the bridge of the guitar. This damping approach caused a reduction in decay time at the targeted modal frequency between 20 and 40ms. Levin noted that this approach is likely more suitable for active control of percussive guitar techniques, as the effect is likely to be less perceivable when playing the guitar's strings.

5.2 Control or Negotiation?

There was a general idea amongst the participants that the interaction with the system felt like a negotiation rather than a conventional exertion of control over the interface (as one may initially expect when considering a human-computer interface). Instead it felt, as described by Abhiram and P6, that the interface was in some way "alive". Abhiram also noted that for equivalent piezoeletric-based sensing mechanisms: "If you don't feel it vibrating, then there's something missing, some, some key, crucial element missing from the instrument."

This concept has been explored previous in literature researching feedback instruments. In Bowers and Haas' work [9] they contrast the usual expectation of touch as a means to actuate an instrument with their work on hybrid resonant assemblages in which touch is "a tension between expressive and destructive potentialities". Mudd et al. [57] remark on the importance of "edge-like interaction", where interactions close to critical thresholds (such as close to unstable feedback) can produce interesting and unusual results. Eldridge et al. [22] describe interaction with self-resonating feedback instruments as having a 'dialogue' with the instrument. This idea is shared by Miguel in the study, who describes interaction with the cello as 'surfing' rather than controlling.

5.3 Use of Damping

The mechanical damping parameter was used by some, but not all, of the participants. Clemens mapped the damping parameters directly to the damping control of the cymbal model plugin, describing it as "super helpful and super intuitive to incorporate in the model", with the intuitive physical analogy providing a direct acoustic equivalence. Clemens extended this interaction in the physical domain by adding foam to the base of the transducer: "it's actually nice to have some travel when you when you push on it", allowing finer control over the parameter. P6 used the damping parameter for control of multiple synthesis parameters through complex mappings and Dimitris used it to control the dynamic range of control voltage signals. Abhiram chose not to use the damping parameter. Miguel also did not use it – the transducer was always damped when attached to the cello's body. Similarly, Levin did not use this feature for the same reason - the transducer was mounted within an acoustic guitar.

Eoghan did not use the parameterised damping value, however the change in impedance due to varying damping was still part of the interaction technique. When the actuator is held down, the resonance peak in electrical impedance is reduced as described in Section 3.2 and shown in Figure 4. The feedback cancellation filters are tuned to match the electrical impedance of the undamped actuator; therefore, the effectiveness of the feedback reduction at the resonant frequency is lessened when the transducer is damped. Due to less accurate cancellation, feedback occurs at a lower actuation level. Eoghan used this to sustain feedback when pressing down or bowing the voice coil, describing it as "pushing on the column, you could feed energy into the system and kind of get control over it". Though this is an unintentional interaction technique from the system design, it provides an interesting example of how features of a system can be misappropriated for creative use, avoiding the designed parameterisation of damping and instead using its properties directly within the audio-rate sensing and actuation.

5.4 Technical Limitations as Creative Affordances

It is well known in creative fields that constants and limitations can often assist with creativity; by imposing limitations on a tool or system, the creative involved is forced to find methods of subverting these limitations to create something of interest. The same is true in DMI designs – Zappi and McPherson found that a DMI design with one degree of freedom led to more explorative play than a DMI with two degrees of freedom [84]. Likewise, Gurevich et al. [30] found that musicians developed a range of techniques and variations using a one button DMI interface. Creativity through constraints was also exhibited by the participants using the HaptiCoupler – particularly with the latency and imperfect feedback cancellation.

The imperfect cancellation between actuation and sensing could lead to self-oscillation feedback when the actuation level was increased beyond the threshold of stability. Eoghan and Abhiram experimented with additional mitigation techniques - such as a small linear frequency shift – this reduces the gain at a single feedback frequency [75]. Eoghan also explored using the pitch shift as a glissando effect, where the feedback loop "excites higher and higher partials and then disappears", along with using damping to induce feedback as described in Section 5.3. Miguel embraced the imperfections of feedback cancellation by explicitly developing feedback-based interactions, describing technical limitations as "just an excuse for transgression to, you know, overcome or compensate in some creative ways".

Additionally, the latency of the system's USB audio interface imposed additional constraints. Dimitris explored using the inherent system latency to create pure data patches that had "more experimental and just kind of chaotic, feedback, wacky loop path" behaviour, incorporating the latency into the self-sustained feedback loop as an additional delay. Eoghan used the latency to infer the rhythmic timings of interaction in order to "hit it, and then wait to feel the feedback, and then let that kind of dictate where the next hit comes". Levin avoided this constraint altogether by implementing processing directly on the Teensy 4.0.

5.5 Interface Physicality

The physicality of the system – and the hardware additions created by some of the participants – also affected the creative outcomes of the study. It was noted by Clemens, Eoghan, and Dimitris that a larger interaction area would be desirable – primarily to allow for two-handed interaction and a wider range of interaction techniques beyond finger tapping. Clemens added a large MDF playing surface to enable two-handed finger tapping with palms maintaining contact with the surface to feel vibrations. This also enabled other forms of interaction, noting that "scraping worked, which is also a nice form of interaction". Eoghan added a 3D-printed top to enable bowing, alongside two locations to hit the voice coil, observing that with the additional surface area to hit, "certain areas are more clacky than others". Dimitris did not modify the physical hardware but did note that a large surface would enable an interaction to "better separate the dampening and touching with the striking". On the other hand, Miguel found the size and weight of the actuator made it more difficult to mount to a cello, with a smaller actuator possibly easing the process. The mass of the voice coil itself also affects the high frequency sensing of the transducer – the inertia of the coil reduces its response at high frequencies above approximately 500Hz. Clemens and Abhiram both noted that they were unable achieve nuanced gestural interactions at high frequencies due to this. Additionally, the mass of the voice coil and its restricted ability to sense low amplitude vibrations meant that Levin was unable to achieve one of their initial goals of sensing guitar string vibrations directly through the system.

6 Reflection

From a purely technical perspective, it would be easy to fall into the trap of attempting to create a system that tries to recreate the tactile interaction with a virtual physical object as faithfully as possible – providing some form of "neutral" linkage between the physical and digital domains through which a digital entity can be controlled. Previous research has investigated such systems, creating complex systems that can perform this role with good accuracy [11, 72]. The HaptiCoupler system, however, does not aim to be a perfect recreation of a physical system. On the other hand, eschewing any notion of 'controllability' and recreating a system with purely chaotic behaviour gives no guarantee of musical interest nor even of novelty, given the long history of such systems in DMI research [8, 57]. Instead, the HaptiCoupler system falls somewhere between the two. It does not conform to the simple notion of control – interaction becomes a negotiation between musician and interface. The system is also not a neutral entity; the physicality and technical implementation contribute to the overall interaction [43]. It does, however, maintain a level of control through the negotiation, through which reproducibility of interactions and gestures can be achieved. While the system sits between the two ideas of control and chaos, the designs presented in the study can shift it towards the direction of one or the other – either creating more chaotic interactions through feedback and self-resonance, or maintaining controllability through the usage of traditional mapping paradigms with the input signal and specifically avoiding self-resonance.

6.1 Designing with an Imperfect System

The HaptiCoupler system provides spatial and modal bidirectionality; sensing and actuation are collocated and both use the same modality to sensing and actuate vibrations. Temporally, however, the sensing and actuation signals are still separated due to the latency of the system. This causes a decoupling of sensing and actuating in time, along with introducing the possibility of oscillating feedback loops. In this sense, the outcomes of this study represent some of the design possibilities for a DMI that work towards bidirectional interaction. The outcomes would likely be somewhat different for a system that is closer to also achieving temporal bidirectionality where the system latency is close to zero.

While the prevailing unidirectional paradigms in interaction with DMIs imposes limitations on the interaction outcomes achievable, the design conveniences afforded by a unidirectional system are appealing. Departing from the engineering norm of unidirectionality is not straightforward – the introduction of stable feedback in an imperfect system that exhibits latency requires carefully considered engineering solutions. The outcomes and work created within the affordances of the system, however, show that a bidirectional - even when imperfect - does produce different results to that of a unidirectional system and shifts towards a less 'tidy' view of interaction - where the coupling of musician and instrument takes precedent over previous notions of 'control'. Much as how Reed et al. [67] suggest embracing the "messiness" of electromyography signals for creative applications, the perceived 'messiness' of the sensing and actuation signals, and the cross coupling that occurs using the HaptiCoupler is a phenomenon that can also be embraced creatively. The imposed technical limitations may instead shift focus away from recreation of physical instrument phenomena and towards more novel and experimental instrument designs incorporating the possibilities of feedback. The imperfections of the system, for example, led to Eoghan's interaction technique of pushing on the voice coil to sustain feedback. This technique subverts the perceived limitation of feedback cancellation and instead uses it as a creative affordance.

6.2 Bidirectionality Changes Interaction Techniques

It is notable that in many of the participant's cases, the addition of haptic feedback to the tactile interaction changed how they interacted with the system – generally involving interactions with sustained contact with the system in order to feel the haptic feedback. For example, Clemens designed the resonant surface shown in Figure 6(c) to be used with the palms of both hands resting upon the surface of the interface with the fingers of both hands able to excite the interface through tapping. This enables vibrations to be felt after exciting the resonant cymbal model though percussive tapping. In Eoghan's case, the coupling of haptic vibration to a desk formed part of the interaction, both through vibrating elements on the desk (such as rattling of objects) and the radiation of acoustic output. Miguel mounted transducer to a cello and used interactions where continuous holding of the instrument with small changes in gesture was needed. P6 used the transducer to control parameters that might have otherwise been controlled with a slider or knob-style interface element. The haptic feedback, and non-holding nature of the damping parameter (the voice coil must be held in the same state to maintain the same damping parameter value) meant that continued interaction occurred.

This adjustment of interaction technique suggests that there is a back-propogation from the technical affordances of the system to the interactions and creative designs. Jack et al. [37] found similar results – when musicians had interacted with a DMI with limited mapping for a sufficient amount of time, the vocabulary of gestures used in reduced to the ones deemed most "musically useful". Tuuri et al. [76] also explore the premise of technology influence interaction techniques, coining the term "technology-induced choreographies". In the case of the HaptiCoupler, the addition of vibrotactile feedback likely changes interaction techniques compared to a tactile system without haptic feedback, ultimately producing different musical outcomes.

6.3 Remutualisation of Audio and Haptics

In acoustic instruments, the vibrotactile feedback experienced by a musician and the auditory output from the instrument are inherently coupled; the very same mechanical vibrations perceived in the tactile domain cause the resonating body of the instrument to couple to the acoustic domain and produce sound. Papetti et al. [65] investigated DMI designs with congruent signals fed to the haptic transducers and the audio output. This, they conclude, has a "demonstrated effect to enhance the playing experience and the perceived quality of the interface", re-establishing a "consistent physical exchange" between the musician and instrument. Marshall and Wanderley [46] report users of DMIs with combined audio and vibrotactile feedback describe them as feeling more like "complete" instruments than just controllers. This suggests that there should not only be a close coupling between tactile input and output, but also tactile input, tactile output, and auditory output. The coupling of all three provides the option to remove the domain barriers often enforced by technical systems – treating tactile input, tactile output, and auditory output as intrisically inseparable. To describe this, we borrow the term "remutualise" from Cook [15], to refer to audio and haptic signals once again being a congruent output.

The HaptiCoupler system does not impose a boundary between haptic and audio signals and instead treats both sensing and actuation as audio signals. It also enables the very same actuator to be used for both haptic feedback and acoustic excitation. This lack of a boundary between the two modalities provides additional interaction options. The voice coil included in the system for this study (though used here for haptic feedback) is designed for use as a surface exciter for a flat panel loudspeaker – radiating the output acoustically through a mechanical coupling to a rigid surface. Eoghan preferred interaction with the system when it was placed on a desk rather than holding the voice coil in the air "because it reverberates through the whole desk, and you get loads of low end" and that when discussing the audio and haptic outputs he realised that he was "talking about both of them at the same time because they're intrinsically linked. I can't really separate them from one another". Miguel mentions that the transducer "activates the resonances of the body" of the cello. Similarly, Levin used the system for control of mechanical resonance. This approach affects both the haptic experience of the acoustic guitar (through the visceral vibration response when playing) and the acoustic output. While other participants did not use the haptic transducer for acoustic output directly, the same audio signals were used for both haptic feedback and audio output (except for some of Dimitris's explorations using control voltage signals). Clemens describe haptic feedback and auditory feedback where "the two things just connect naturally" – there is congruence between the two modalities.

6.4 Blurring of the Physical-Digital Transition in Hybrid Systems

Building on the 'remutualised' status of audio and haptics through these designs, the outcomes of the study present a more flexible approach to defining the boundary between physical and digital domains in hybrid systems. Bidirectional force feedback approaches in existing DMI design literature, such as the Plank and the Firefader [77], tend to act as a physical controller for an otherwise digital system; the haptic interaction is in the physical domain but any musical synthesis or resonances are simulated in the digital domain. At the other end of this spectrum is actively controlled acoustic instruments – where the musical output and resonance occurs physically and the digital system performs some form of control (such as altering the resonant decay time) [6, 20].

The outcomes of this study showcase designs across this spectrum, from designs that primarily use the HaptiCoupler as a controller for digital synthesis to designs that use it to control acoustic instruments using digital systems. The work of Abhiram, Dimitris, and P6, sits firmly at the controller end of this spectrum, as does the work by Clemens and Eoghan (though both add additional physical elements to the interface). Levin's work is at the other end of this spectrum, using the HaptiCoupler to control the resonance of an acoustic guitar. Miguel's work sit somewhere in the middle - a feedback system that incorporates both the acoustically resonant cello and digital resonator techniques is used.

The audio-rate signals and the modal and locational bidirectionality provide the ability to flexibly assign where in the musical system the boundary between digital and physical domains occurs. This enables a range of creative outcomes seen in this study.

7 Conclusion

This paper presented a designer study of tactile musical systems, exploring what happens when tactile interaction is not dependent on the unidirectional signal flow models commonly found in engineering systems. Our HaptiCoupler system uses a self-sensing voice coil transducer to create a rich bidirectional tactile coupling between the physical and digital domains, acting as a broadband audio-rate sensor and actuator simultaneously. Amongst other applications, this broadband sensing and actuation enables rich interaction with digital resonator models. The use of audio-rate signals also remutualises the auditory and haptic domains: the mechanical vibrations are intrinsically linked to the sonic output of the system. This further allows flexibility in defining where the digital-physical connection exists within the hybrid system as a whole.

The creative outcomes of the study show a variety of instrument archetypes as well as highlighting the constraints of the system, namely the limited feedback cancellation, high USB audio latency, and limited sensing of high frequency signals. Significantly, the outcomes show how such constraints can be used as creative inspiration, for example by using self-oscillation as a performance technique or playing rhythmically with the system's latency. As discussed in Section 6.1, when the messiness of the blurred system is embraced creatively, the system can add tangibility through vibrotactile feedback that was described as being "natural" and "pleasing" (Clemens) and making the instrument feel "alive" (Abhiram and P6).

The outcomes suggest that we should take a less modular view of technological elements when bidirectionality is introduced: individual components of an instrument system cannot be viewed independently and must instead be considered as part of the larger system. This includes the musician interacting with the system, whose role transitions from that of controller to one of negotiator – the instrument system feels "alive" and pushes back on the musician. In this sense, de Campo's [17] idea of losing control while gaining influence is enacted: complete control is relinquished and the musical system gains a degree of agency, even as the result remains distinct from the unpredictable exploratory systems often found in digital music research. Within broader human-computer interaction, this moves towards Mueller et al.'s concept of 'intertwined integration', where agency is shared between the human and machine [58]. Like a performer playing an acoustic instrument, outcomes and behaviours become difficult to attribute solely to either human or technology, instead emerging from their close combination.

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