The HaptiCoupler: Self-Sensing Haptic Feedback for Tactile Musical Interaction

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***Abstract*— The HaptiCoupler system enables simultaneous tactile sensing and vibrotactile haptic actuation using a single voice coil transducer. Designed for interaction with synthesisers, this enables sensing of gestures such as taps and hits, alongside sensing the continuous pressing on the surface of the voice coil, while feeling the audio output of the synthesiser on the fingertip. The system has the potential to bring more realism to digital synthesisers, through its audio-rate sensing and haptic feedback, while also creating opportunities for novel synthesis and music creation techniques.**

I. Introduction

Digital synthesisers are capable of creating a near-infinite array of sounds, yet interaction with them is often limited to the capabilities of MIDI (musical instrument digital interface) keyboards. The MIDI standard, dating back to the 1980s, requires musical gestures to be classified and discretised into distinct events (such as 'note on' and 'note off'), through which synthesis is then performed. While this ensures inoperability between devices, gestures are limited by the standard. More recently, audio-driven synthesis has gained popularity as a technique for more expressive interaction in digital musical instruments (DMIs). These synthesisers take an audio input (from devices such as microphones or piezo contact pickups) and use this signal to excite a digital resonant model. This model will often recreate the sound of physical musical instruments, such as a string using the Karplus Strong algorithm [1]. By removing the discretisation and gesture classification required by MIDI, a more intimate control is possible. For example, using a piezo contact pickup on a surface to excite a digital snare drum model, scratching the surface will sound very different to tapping the surface [2].

While audio-driven synthesis may offer more intimate control of digital synthesisers, it still doesn't offer haptic feedback to the musician which can limit the sensing of realism – the vibrations normally present in acoustic instruments are still missing. The main reason that audio-driven synthesisers rarely implement vibrotactile haptic feedback is due to unstable crosstalk; the haptic feedback disrupts the audio sensing signal which can cause unwanted feedback [3].

The HaptiCoupler system enables haptic interaction with audio-driven synthesisers through simultaneous sensing and actuation with a single voice coil transducer. This means that a musician can simultaneously interact with the synthesiser through gestures (such as tapping the coil) while feeling the vibrotactile feedback generated by the audio output of the synthesiser. Additionally, the continuous pressure applied to the voice coil can be sensed by measuring the change in the voice coil's electrical impedance. These modalities are shown in the figure below (taken from [8]).

(a) Vibrotactile Actuation (b) Vibration Sensing (c) Damping Sensing

The system mitigates the issue of feedback by using the same device (a voice coil transducer) as both a sensor and actuator simultaneously. By actuating with voltage and sensing with current (cancelling the cross-talk due to Ohm's law with basic signal processing) the issue of unstable feedback can be alleviated. This means that audio-driven synthesisers can be excited (by tapping the coil, for instance) while feeling the feedback of the vibrations from the synthesis.

II. Related Work

In the New Interfaces for Musical Expression (NIME) community, there is a significant history of DMIs with haptic feedback, both force feedback (where motors are used to exert force upon the user) and vibrotactile (where vibrations within the device are actuate) [4]. These devices, however, are almost always either limited to a single or small handful of prototype devices. Few devices maintain longevity beyond an individual's own creative practice – an issue that is often shared across the NIME community [5]. There have also been many previous examples of audio-driven synthesis systems, with greater proliferation into commercial products. Notable examples include the Korg Wavedrum and modular synthesis modules such as the CHAIR Audio Analog Waveguide, yet this area remains under-explored.

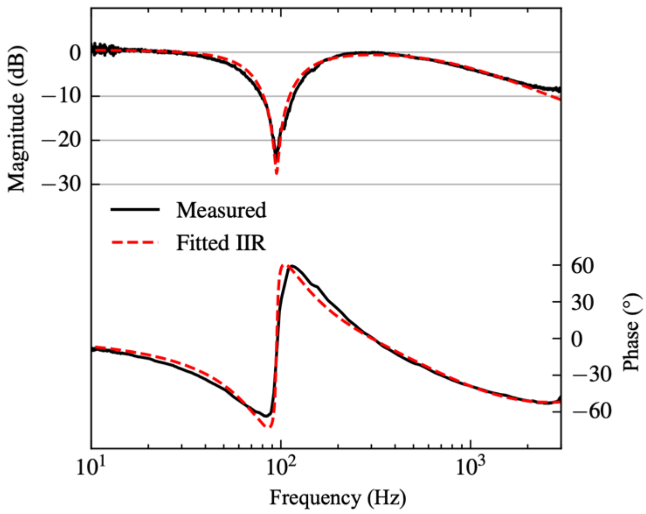
Beyond DMIs, there are examples of self-sensing actuator methods used in haptic feedback devices within human-computer interaction literature [6]. In these cases, the self-sensing approach can lower the complexity of designs and enable perfect collocation of sensing and actuation, as well as providing additional sensing data compared to traditional methods [7].

III. The HaptiCoupler System

A. *Overview*

A brief video overview of the HaptiCoupler system can be found here: https://youtu.be/O2G3ud8Zfns. In a previous design research study, participants used the system to design a variety of musical interfaces including a feedback cello, a bowed haptic interface, and a percussion interface [8]. Selected example outcomes from the study are pictured below.

The HaptiCoupler actuates with voltage and senses with current. A voltage signal causes the voice coil to vibrate and, conversely, movement of the coil induces a current. Of course, voltage and current are related due to Ohm's law – the actuation voltage will also induce a current in the coil. The current induced due to the actuation voltage will be proportional to the voice coil's electrical admittance (the inverse of impedance). By measuring the transducer's admittance, it can be modelled using digital filters. This is shown in the figure below, where the measured impedance (measured by the HaptiCoupler system) is plotted against the modelled impedance using digital filters.

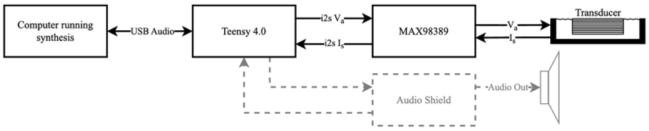


This filtering is applied to the actuation signal and then subtracted for the current sense signal. This reduces the level of the crosstalk between actuation and sensing – leaving the sensed current due to external forces (such as tapping on the voice coil) unaffected.

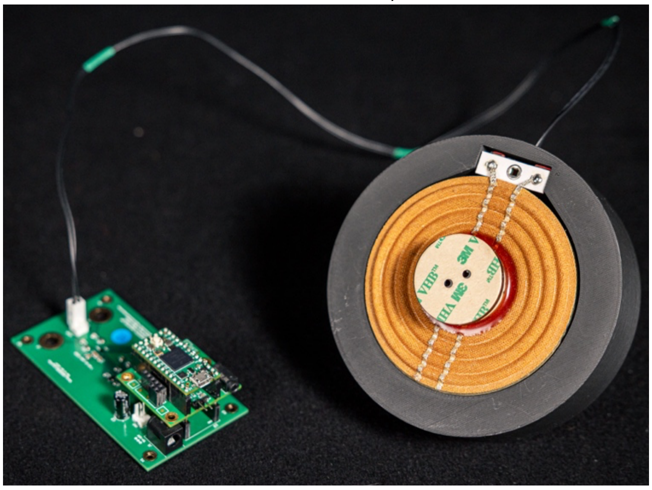
The HaptiCoupler system is open source and the current design (hardware and firmware) is available at: https://github.com/davisonaudio/HapticInstrumentWorkshop

B. *Current Design Implementation*

The current HaptiCoupler system consists of three main electronic components: a Teensy 4.0 microcontroller, an Analog Devices MAX98389 class-D audio amplifier IC, and a voice coil. The MAX98389 has digital audio (I^2S) I/O, avoiding the need to use a separate DAC. The amplifier also provides a real-time current sensing feedback (at audio-rate and also over I^2S) which is used for self-sensing. I^2C is used to configure the amplifier. A Teensy 4.0 microcontroller board is used to configure the amplifiers and send/receive I^2S audio signals, as well as performing the required signal processing for feedback cancellation and damping sensing. The Teensy also provides USB and analogue audio connections for connecting to external synthesisers, along with USB MIDI for additional parameters and USB serial for configuration of the device via a web interface. A basic overview of the system, when USB audio is used, is show in the diagram below.

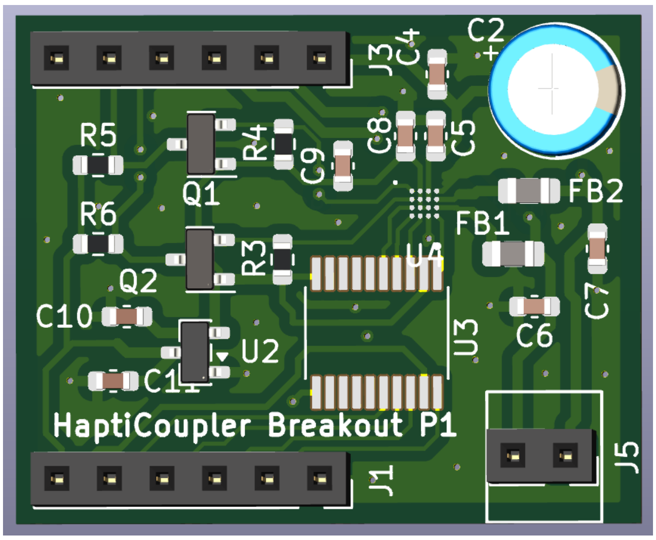


The current version of the system, with a Dayton Audio EX32VBDS-4 voice coil transducer, can be seen below.



C. *Proposed Future Designs*

The next iteration of the HaptiCoupler system will involve three tiers of devices, for different applications. The most basic device will be a simple breakout development board (effectively a breakout board for the MAX98389 IC) with accompanying drivers and examples for common embedded audio processing platforms (such as Teensy, Daisy Seed, and Bela). A prototype design of this board can be seen below.



The second tier will be a further refined version of the HaptiCoupler system used in previous research. This will be a complete platform (including microcontroller) that performs the necessary base level of signal processing. This system can then be connected to existing synthesiser and the hardware modified, similar to the outcomes explored in the previous user study . The third tier will be a complete self-contained system which can function as a standalone synthesiser. This will be based on the second tier board, with an add-on PCB for additional interface elements (such as buttons, potentiometers, and a small OLED display) along with a voice coil. All of this will be housed inside a single enclosure, likely manufactured using 3D printing techniques.

By creating three versions of the product (re-using much of the hardware and firmware design across the three) it caters for a wider range of individuals – embedded hardware enthusiasts who want to integrate it into their own embedded systems, DIY musicians who want a certain level of customisation and modification options, and electronics musicians who want a ready-to-use synthesiser. Additionally, it provides flexibility for extended use cases – such as using the hardware as a loudspeaker analysis tool.

IV. Responsible innovation

The HaptiCoupler system is designed to be modular and all elements are open source. This increases the likelihood of repairs, modifications, and reuse which reduces electronic waste. The system is designed for longevity and uses open standards (such as USB MIDI/Audio) which reduces reliance on custom device drivers which, if not updated, can cause products to become obsolete. Additionally, the development versions of the allows for the re-use of existing loudspeakers, allowing DIY musicians to repurpose existing components into new interfaces.

V. Author bio(s) / experiences

Matthew Davison is a PhD student within the Augmented Instruments Lab at the Dyson School of Design Engineering, Imperial College London. His research is centred on haptic feedback and bidirectional interactions between the physical and digital domains within digital musical instrument designs. This involves the creation of the HaptiCoupler system – to explore how DMI designs are changed by bidirectional tactile interaction – alongside exploring other novel sensing and actuation techniques [9]. Prior to this, he was an embedded software engineer at DiGiCo, designing digital live sound consoles, including their latest flagship product. This included working on bare metal and RTOS systems, interfacing with FPGAs, and control of physical interface elements such as motorised faders and LCDs.

VI. Acknowledgements

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VII. References

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