Techniques for Closely-Coupled Sensing and Actuation in Digital Musical Instruments

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

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

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

Abstract

Musical instruments involve numerous bidirectional couplings, between the musician and instrument in the tactile domain and between elements of the instrument's mechanical system. Closely-coupled sensing and actuating – where the two are simultaneous, collocated, in the same modality, and frequency range – can enable the design of hybrid instruments that fluidly exist across physical and digital domains. This, however, can introduce issues of crosstalk between actuation and sensing as well as unstable feedback if the implementation is not carefully considered. This paper summarises techniques for achieving closely-coupled sensing and actuation in digital musical instrument design. Options for reducing and mitigating interference between sensing and actuating are discussed, with their potential affordances of particular applications within hybrid instruments explored.

Keywords

Actuation, Sensing, Hybrid Instruments, Feedback Control, Bidirectional

1 Introduction

Interacting with a musical instrument will often involve a plethora of bidirectional couplings of different forms. From an embodied cognition point of view, the physical interaction between the musician and the instrument forms a coupling – the musician can affect the instrument, but the instrument's physicality will affect the musician's movements in return [38, 60, 63]. There exists an exchange of energy and information between the instrument and the musician [41, 53]. There also exist physical couplings within acoustic instruments, facilitating energy transfer and mutual dependencies. The bridge of a violin, for instance, transfers the energy of the vibrating strings to the body of the instrument; while conversely, the mechanical impedance of the bridge and the body will also determine how the strings vibrate, coupling the system together. Similar couplings occur in wind instruments between the mechanical and acoustic domains; changes in the acoustic impedance of the air column within the instrument and changes in the vibration of the reed both mutually affect each other [8]. The behaviour of the individual elements cannot be modelled or predicted without first knowing (or modelling) the state of all of the other coupled elements.

From this, we define a *close coupling* as a connection with a continuous and bidirectional flow of energy; where the causality of any particular behaviour cannot be attributed to one single element due to the interdependencies of the system.

When designing acoustic instruments, these couplings (in their various forms) tend to form an intrinsic part of the instrument design. With sufficient computing power, it is also possible to produce simulations of these acoustic instrument couplings in the digital domain in real time [9]. A more challenging task, however, is creating close couplings *between* digital and physical domains. Engineering conventions enforce some level of unidirectionality for convenience and performance reasons – particularly at the boundary between domains e.g. between analogue electrical signals and the digital system [62]. Unidirectionality brings many technological benefits, such as allowing the system to be modular without concern for mutual dependencies between modules. While providing engineering convenience, this convention restricts the creation of systems that can mutually couple between physical and digital domains, influencing and limiting the creation of hybrid DMI designs [48].

1.1 Requirements for a Closely-Coupled System

Within this paper, we borrow concepts from NIME-adjacent literature to describe established techniques for achieving closely-coupled sensing and actuation and overcoming the convention of unidirectionality. Drawing from ideas introduced by Strohmeier et al. [61] and considering the definition of a close coupling introduced previously, we define an ideal 'closely-coupled' system to be where the sensing and actuating are:

1. Collocated
2. Using the same modality
3. Simultaneous
4. Of the same frequency bandwidth

While, in reality, many systems break one or more of these requirements, these initial four ideals give ground to assess the techniques suggested in this paper. Some techniques have been explored in existing DMI designs and others can be appropriated from different domains of research. This paper gives an overview of the possible uses of close-couplings in DMI design and possible techniques and design considerations for implementing closely-coupled sensing and actuation.

2 Musical Applications of Close Couplings

Closely-coupled sensing and actuation is a particularly important aspect of hybrid instrument designs where part of the instrument is in the physical domain and another in the digital domain. Many of these designs use a unidirectional connection between domains; sensing a gesture to be used as the input to a digital synthesiser is a commonly used example of this [67]. Alternatively this unidirectionality may instead go from the synthesis system *to* a physical system, such as the 'diffuseurs' of the ondes Martenot – resonant objects that are excited by the synthesis output [69].

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Hybrid instrument designs may also have bidirectionality between domains where there is no closely-coupled sensing and actuation involved – either where there is a separation between sensor and actuator [15] or where the sensing is performed at a lower 'control-rate', often involving some form of signal discretisation. While these techniques can produce a range of interesting interactions and sonic outcomes, this is still different to the techniques explored in this work. Here, we focus on systems and applications where there is tightly-coupled exchanges of energy between domains.

2.1 Haptic Feedback

Two main forms of haptic feedback exist within DMI designs: vibrotactile feedback and force feedback. Vibrotactile feedback creates vibrations primarily targeting the tactile sense of touch, whereas force feedback uses actuators to exert a force or velocity and primarily targets human kinaesthetic sensing [30].

Force feedback haptics has been extensively studied in the context of DMIs [27, 68] and also tends to involve a closely-coupled sensor-actuator pair, generally operating under a closed-loop control process. By controlling the relationship between sensing and actuating, different sensations can be created such as interacting with hard shapes or textured surfaces. These virtual objects often use some form of physical modelling to calculate an actuation output for a given input.

Vibrotactile feedback has also been included in many prior DMI designs [44, 55]. Not all vibrotactile haptic feedback DMIs involve closely-coupled sensing and actuation; many use decoupled sensing mechanisms or provide symbolic haptic feedback (conveying the state of a synthesis parameter, for instance). In cases where audio-rate vibration sensing is used, however, this can constitute a closely-coupled system and must be designed carefully to avoid interference or unstable feedback [15, 19].

2.2 Active Control

Active control, whereby a digital or electronic system alters behaviour of an otherwise acoustic instrument, is another area of instrument design where closely-coupled sensing and actuation is of particular importance. In general, active control systems will sense the state of a musical instrument at a particular location and use some form of control system to produce an output upon the physical instrument using an actuator [2]. This can control timbral characteristics such as the decay time of resonant modes, and has been implemented on a variety of instruments such as string instruments [4, 22], a simplified bass clarinet [51], a trombone [52], and a conga [65]. Stability is a particularly important concern for active control systems – the control loop must ensure that feedback from the actuator to the sensor does not cause the system to become unstable. Stability and accurate control is usually more attainable by using collocated sensors and actuators [2, 42].

2.3 Self-Resonating Feedback Instruments

Self-resonating feedback instruments intrinsically involve coupled sensing and actuation; the feedback loop formed between the sensor and actuator achieves a high enough loop gain to cause the system to self-resonate [23]. In most feedback instruments, some form of signal processing is conducted between the picked-up signal and the amplifier that powers the actuators to make the feedback more controllable or 'sonically interesting' [12, 33, 50]. The requirements for a self-resonating feedback system are often less rigid than the closely-coupled sensing and actuating requirements described in this paper. There does not need to be a well-controlled stable control loop between sensing and actuating – the very purpose of the sensing and actuating is to reach instability. In fact, in many cases, the sensor and actuator are intentionally placed in separate locations upon the resonant surface of the instrument to reduce the direct coupling from actuator to sensor. Despite this, the techniques presented in this paper have the potential to be explored within the design of self-resonating feedback instruments.

3 Techniques to Enable Close Couplings

While an ideal close coupling should sense and actuate in the same frequency range, location, modality, and do so simultaneously, in practice this is not usually achievable due to a number of technical limitations. Practical techniques will often involve breaking one (or more) of these ideals, with the selected approach determined by the requirements of the particular use case. This section explores techniques from literature within and outside of the NIME domain, looking at particular techniques and when they may be used effectively.

Often in DMI literature, particularly in self-resonating feedback instrument designs, simultaneous sensing and actuation involves transducers that are separated in location (as well as often modality). While this is done with intention and can lead to interesting sonic outcomes, as described in Section 2.3, we do not consider such techniques further in this paper due to the removal of the collocation constraint.

3.1 Time-Division Multiplexing

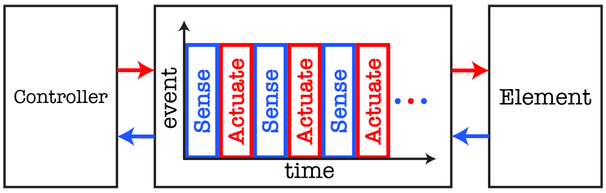

Figure 1: A representative diagram of a system using time domain multiplexing; the system alternates between sensing and actuating for each timeslot. The element is the physical assemblage being sensed and actuated while the controller is the digital, or electronic, subsystem.

When performing collocated sensing and actuation in the same modality, the sensed signal is likely to pick up the actuation signal applied to the transducer (i.e., cross-talk). One method of mitigating this is to perform time-division multiplexing (TDM) between sensing and actuating modes, as shown abstractly in Figure 1. This method relies on switching between sensing and actuating in time. Although this breaks the requirement of simultaneous sensing and actuation proposed in Section 1.1, if the multiplexing is performed at an appropriately high frequency for the bandwidth required by the system, then it can still effectively function as 'simultaneous'.

A widely used example of a TDM sensing and actuating approach is medical ultrasound imaging devices. These use arrays of piezoelectric elements that are first treated as actuators to send out ultrasonic chirps [17]. Then, the circuitry connected to the elements is switched to use the elements as sensors, converting the reflections of the ultrasonic chirps back into an electrical signal. The controller then interprets the amplitude and time differences in the received signals to generate a two or three-dimensional image.

An example of a haptic feedback system that uses TDM sensing and actuation is the Magnetips system by McIntosh et al. [46]. An array of magnetometer sensors monitor the position of a small permanent magnet fixed to a user's fingertip while an electromagnetic coil applies haptic feedback to the same magnet. An example of a musical instrument that uses TDM is the Moog Guitar[1]. This instrument uses a special case of TDM to employ a single, low-inductance electromagnetic coil as both a sensor and an actuator to control vibration of a ferromagnetic guitar string.

The strength of force that can be generated from such coils is proportional to the current through the coil and the number of windings in the coil. Although increasing the number of windings in a magnetic solenoid coil can increase the maximum force applied to an element, the rate at which a coil dissipates its electric current is directly related to its inductance, which is directly related to its number of windings. A higher inductance means the coil takes longer to charge up and dissipate a current. Without any TDM intervention, McIntosh et al. verified the electromagnetic crosstalk between their haptic actuation coil and magnetic sensor array when attempting to sense and actuate simultaneously. Implementing time-division multiplexing allowed time for the actuation signal's magnetic field to dissipate before attempting to sense with the magnetometer array. Each time the coil was actuated with a current, the system waits two milliseconds from the end of an actuation event before attempting to sense.

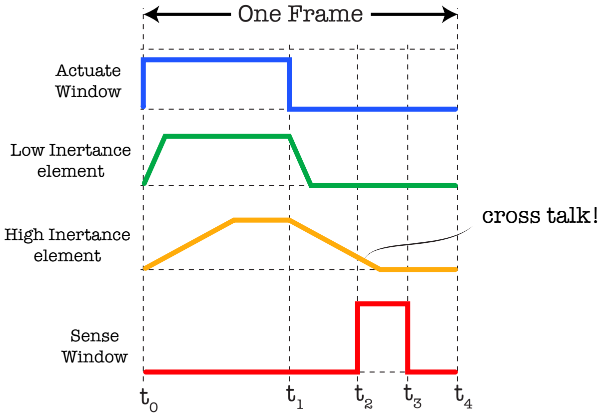

Figure 2: Preventing crosstalk between actuation and sensing events is a tradeoff between transducer inertance and sample rate

The mechanical analogue of inductance is *inertia*, but this concept can be generalized across domains (electrical, mechanical, acoustic, etc.) as *inertance*. Figure 2 shows an example timing diagram of a TDM approach. Within each frame, the system alternates between actuating and sensing an element. From t_0 to t_1 is the actuation event when the controller applies a force to the element. Between t_1 to t_2, the system waits for energy to dissipate from the element and hopefully facilitates full isolation between sensing and actuating signals. Between t_2 to t_3, the system senses the state of the element. In the case of the Magnetips, The minimum settling time reveals the trade-offs between the properties of the actuator (e.g., the inductance of the coil), the properties of the controller (e.g., the maximum force feedback), and the maximum frame rate of the system dictating bandwidth of both the sensor and actuator.

Due to this, TDM is most suitable for situations with low-inertance elements when used for audio-rate feedback. For example, our recent work in string actuation uses conductive instrument strings as sensors and actuators directly (through Electromotive force sensing and Lorentz force actuation) and avoids the high inductance of coils altogether [57]. By using the string as the transducer, it effectively forms a single turn inductor (and therefore has a very low inductance). In this work, the actuation takes approximately $20\mu s$, with a further $20\mu s$ delay (to reduce crosstalk), followed by approximately $10\mu s$ to sense. This gives a total period required to sense and actuate of $50\mu s$. The total sense and actuate period dictates the operating bandwidth; a smaller total period enables the system to have a wider bandwidth.

The transducer inertance also limits the force that the controller can exert upon the element. Looking at Figure 2, the controller only has the opportunity to actuate from t_0 to t_1. If inertance is increased with the same total sense and actuate period, then this 'actuate window' must be decreased, limiting actuation output. Putting this in terms of power, if the maximum actuate duty cycle is only 20% of the frame period, then a 5-Watt actuator only has $5W \times 20\% = 1W$ effective power, limiting the actuation force to a fraction of what it may be under other approaches.

It should be noted that the high inertance of the *transducer* is problematic for TDM and not the inertance of the physical element (such as a string). In the case of the Moog Guitar (and self-resonating feedback instruments in general), the frequency at which a string vibrates is directly tied to its mass and therefore also inertia (mechanical-domain inertance). The controller must be designed to mitigate the effect of inductance of the *transducer* (i.e., electrical-domain inertance) while measuring and affecting the mechanical state of the *element*.

3.2 Frequency-Band Separation

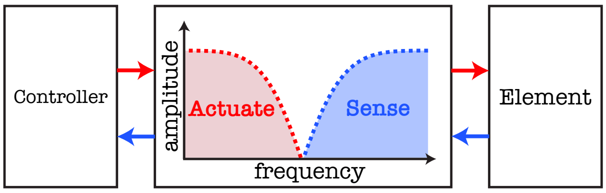

Figure 3: A representative diagram of a system using frequency-band separated sensing and actuation. Filtering of the two signals ensures that sensing and actuating occur in mutually exclusive frequency bands. The element is the physical assemblage being sensed and actuated while the controller is the digital, or electronic, subsystem.

Another approach to achieving simultaneous sensing and actuating in the same modality is to use separate frequency bands for sensing and actuating. For systems that behave linearly, the sensing and actuating can be separate by filtering the respective signals. An example of this is depicted in Figure 3, where actuation is performed in a lower frequency band than sensing. This method is particularly useful for systems that utilise active

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[1] https://en.wikipedia.org/wiki/Moog_Guitar

sensing methods, as described in Section 4.3. This method has previously been explored in numerous human-computer interaction systems, often using sensing via ultrasound to avoid interference with audible output from the device [34–36]. Laput et al. [35] created passive tangible elements that mount on a smartphone. The mechanisms form pipes that route between the smartphone's loudspeaker and microphone and offer tangible elements – such as switches and sliders – that alter the pipe pathway. Ultrasonic frequency sweeps are emitted by the loudspeaker and measured by the microphone. This enables the structures to be used as tangible interface elements, while the use of ultrasonic signals prevents the active sensing from being audible and also allows the potential for the speaker to additionally be used for audible output. Laput et al. [36] use a similar method to detect whether earbuds are inserted into the ear – using the earbuds themselves to actuate an ultrasonic sweep and the in-line microphone to sense the signal. In this case, the frequency spectrum is further divided to enable to detection of each earbud individually – using a 20-22kHz sweep for the left earbud and 23-25kHz for the right.

In haptic feedback literature, Gratz-Kelly et al. [28] created a dielectric elastomer self-sensing actuator that is capable of haptic feedback, acoustic output, and touch sensing. Frequency separation is applied between the haptic actuation (at low frequencies) and the acoustic output and self-sensing (at high frequencies). Youn et al. [71] use a microspeaker perform hydraulic actuation of vibrotactile signals between 1-500Hz while sensing the change in inductance of the speaker at 3MHz to detect touch input.

Within DMI design, Davison et al. [19] used frequency band separation techniques (alongside additional cancellation methods) to perform active sensing at the resonant frequency of a self-sensing voice coil transducer for haptic interaction. A notch filter is applied to the haptic actuation signal at the resonant frequency (f_0) of the transducer and a constant sine tone at frequency f_0 is added to the actuation signal to enable active sensing of the damping of the transducer.

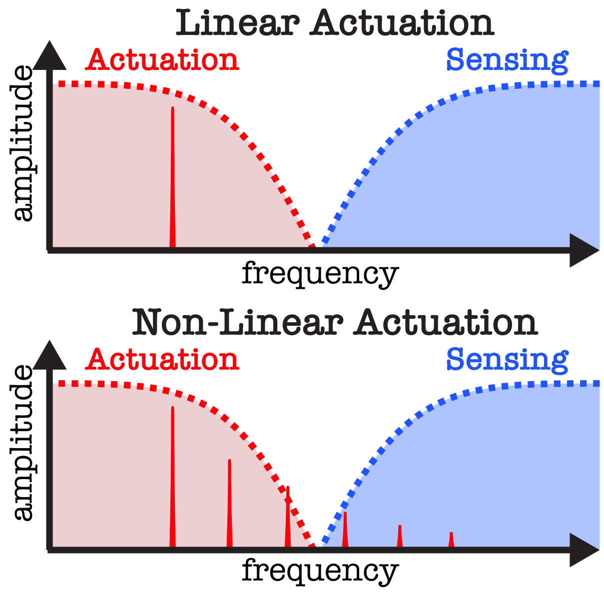

Figure 4: An example graph of frequency-separated actuation and sensing showing the importance of linearity in actuating.

An additional consideration for frequency-band separation techniques is the linearity of the system. For linear systems, appropriate filtering of the actuation and sensing signals can ensure sufficient separation between the two. In systems where the actuator exhibits significant non-linearities, however, the technique may be less suitable, as the harmonics generated by the non-linearities may disrupt the sensing process. This is shown in Figure 4, where the non-linearities from the actuator are present in the sensing frequency band in the bottom graph. Laput et al. [35] mention that the performance of their ultrasonic sensing deteriorates when the phone speaker is used for audio-band output simultaneously, attributing this to additional harmonics from the audio. They suggest some form of varying time-division multiplexing – where the sensing is only performed when the audio output level is low – as a possible mitigation method.

While frequency separation is a technique that is particularly well suited to certain forms of interaction and control interfaces, it is less suited to applications such as feedback instruments and active control. This is due to the evident limitation that sensing and actuating occur in mutually exclusive frequency ranges and therefore a signal sensed at a particular frequency is unable to be modified by the actuator. Overall, frequency separation techniques are likely best suited to haptic feedback or tactile interaction applications.

3.3 Impedance Approaches

While it is common to use separate transducers to sense in different modalities, self-sensing transducers may be used where the conjugate variables of current and voltage are used, one to sense and the other to actuate, discussed further in Section 3.3.1. If the pair of transducers (or single self-sensing transducer) is used for tasks beyond self-resonating sustain, such as active resonance control, the system usually has to be characterised – with a known transfer function between actuator and sensor to account for crosstalk. While this is often possible, particularly if a system has a low order transfer function, the linearity of the system's components is of importance. System models that account for non-linearities can be used however this often significantly increases the complexity of processing and, in practice, the assumption of a linear system is often made. If the sensors, actuators, or amplification circuitry used in the design exhibit significant non-linearities, these will not be accounted for in the system transfer function, making the separation of the sensing signal from the crosstalk more challenging.

The distinction is made in this section between electrical, mechanical, and acoustic impedance approaches. While they each operate in different domains, many similarities exist between them. Drawing on Port-Hamiltonian modelling approaches (which provide unified methods of modelling cross-domain systems), each domain has an 'effort' variable (e.g. voltage in the electrical domain, force in the mechanical domain, pressure in the acoustic domain) and a 'flow' variable (current, velocity, and volume velocity in their respective domains) [64]. Multiplied together, they form power. The relationship between the two variables is described by the system's impedance or admittance [24].

3.3.1 *Electrical Impedance.*

When using bidirectional transducers such as voice coils or piezoelectric transducers, self-sensing can be achieved by using the port variables of voltage and current; one used to sense and the other to actuate, as shown in Figure 5. This, however, does not solve issues of crosstalk between actuation and sensing signals. Time-multiplexing between actuation

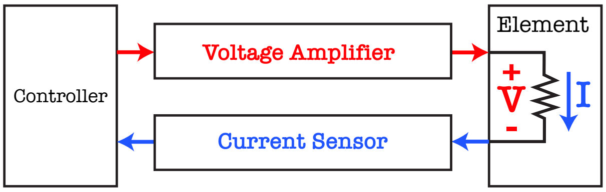

Figure 5: A representative diagram of a system using electrical impedance – either actuating with voltage and sensing with current or vice versa. The element is the physical assemblage being sensed and actuated while the controller is the digital, or electronic, subsystem.

and sensing (as discussed in Section 3.1) could be implemented to overcome this - disabling the actuation when sensing [21]. Alternatively, when actuated with a voltage and sensed with a current (or vice versa), crosstalk can be modelled and cancelled from the sensing signal. Such an approach enables truly simultaneous sensing and actuation using a single transducer. The voltage and current are related due to the electrical impedance of the transducer and Ohm's law, therefore the transfer function of the crosstalk between sensing and actuating will either be the electrical impedance (for current actuation and voltage sensing configurations) or the electrical admittance (the inverse of impedance, for voltage actuation and current sensing applications).

This technique of using voltage and current for sensing and actuating has been used in a variety of fields - particularly with electromagnetic and piezoelectric transducers. In DMI design, the authors have previously used a voice coil transducer as both a sensor and actuator to excite a physical modelling synthesiser [19]. The audio-rate voltage provided an excitation signal and a current amplifying provided vibrotactile actuation from the synthesiser's output. The actuating signal is cancelled from the sensing signal by applying a second order filter approximation of the electrical impedance. In our subsequent work, a similar approach is used in the HaptiCoupler system created by the authors [18]. This time, the roles of voltage and current are swapped (using current to sense and voltage to actuate) as commercial components with voltage amplification and current sensing are more commonly available. In haptic feedback technology and HCI, Dementyev et al. [20] use current sensing with a voltage amplifier and a linear resonant actuator (LRA) to sense pressure on a mobile phone while simultaneously providing vibrotactile haptic feedback.

Manabe and Fukumoto [43] sense the current in earbud speakers to detect finger taps on the outside of the earbud when listening to music. In this example, the voltage actuation signal is subtracted from the measured current to reduce actuation to sensing crosstalk. The level of subtraction signal is adjusted manually for the specific headphones. Oshima et al. [54] use a similar analogue-domain approach when cancelling the actuation signal from a loudspeaker to simultaneously use it as a microphone. Instead of digital modelling the loudspeaker's impedance, two identical loudspeakers are used, acoustically isolated from each other and driven with the same voltage signal. The current from the isolated speaker is subtracted from the current of the other speaker to obtain the sensing signal. This approach assumes that the two loudspeaker impedances and any non-linearities are identical.

Continuing in active acoustic and vibration research, both electromagnetic transducers and piezoelectric transducers have been used in self-sensing configurations for active damping of resonances. These systems connect the transducer to an electrical impedance – this can either be using analog electrical components or a synthesised impedance using digital signal processing (DSP). Configurations using analog components have used both passive networks of components and active components – which can be used to generate negative impedances to account for the electrical impedance of the voice coil [10, 14]. Synthetic impedances generated using DSP have been used to simulate more complex networks of electrical components or offered real-time adjustment of impedance [25, 26, 29, 45]. Due to the bidirectionality of the transducers involved, the electrical components couple to the mechanical and, subsequently, acoustic domains. Changing the electrical impedance of the circuit alters the acoustic impedance and vice versa. Similar techniques of synthetically generating electrical impedances using DSP have also been used for creative audio processing purposes – enabling digital reconfigurability of synthesised components in an otherwise analog electrical circuit [7].

3.3.2 *Mechanical Impedance.*

There exist two primary manifestations of mechanical impedance approaches in closely-coupled sensing and actuating systems: force feedback haptics and active control of mechanical vibrations.

Force feedback haptics uses the mechanical impedance variables of force and velocity to sense and actuate, in order to simulate the presence of mechanical objects or textures as the user interacts with the device. Impedance-based force feedback haptics senses velocity (or derives it from displacement) and actuates a corresponding force whereas admittance-based force feedback operates in the opposite manner – sensing force and actuating a velocity [32]. The main considerations when choosing to implement either impedance or admittance force feedback are the available sensor and actuator combinations (and what parameter they sense or actuate) and the desired stiffness of the objects to be simulated. Admittance-based controllers are better suited to rendering stiff virtual environments whereas impedance-based controllers are more suited for low-stiffness rendering. In either approach, the control loop must also limit actuator output to ensure stability [1].

Force feedback has been extensively studied in DMI design for several decades, beginning with the work of Cadoz et al. [13]. Subsequent notable examples of force feedback haptics in DMI design include Verplank et al. [66], who used the voice coil actuator from a hard drive armature together with its magnetic encoder for position sensing, and Berdahl and Kontogeorgakopoulos [3] used a motorised fader for force feedback haptics with physical modelling synthesis, using the fader as a displacement sensor and the DC motor as an actuator.

Active control of mechanical vibrations can also be achieved using sensors and actuators to affect a mechanical impedance. As discussed in Section 3.3.1, this can be implemented using a self-sensing actuator and varying the attached electrical impedance. It can also be implemented using separate sensors and actuators, such as a collocated accelerometer and voice coil surface transducer [42].

3.3.3 *Acoustic Impedance.*

Similarly to mechanical impedance approaches to active control, acoustic impedance approaches can also be implemented using self-sensing actuators and an appropriate electrical impedance (either in the analog domain or synthesised by the digital domain). Boulandet [11] make use of this to measure changes in acoustic impedance by measuring the change in a loudspeaker's electrical impedance alongside a model of the loudspeaker's parameters. They find that changes in the acoustic domain can be detected in the electrical domain, but only around the resonance of the transducer (where the transducer is most efficient).

Acoustic impedance approaches may often use a separate sensor and actuator, often with a microphone to measure pressure and a loudspeaker to actuate a volume velocity. Meurisse et al. [52] use this approach with a collocated microphone and loudspeaker within a trombone mute, with a control loop used to enact active control that account for the mute's changing of the trombone's acoustic impedance.

3.4 Different Modalities

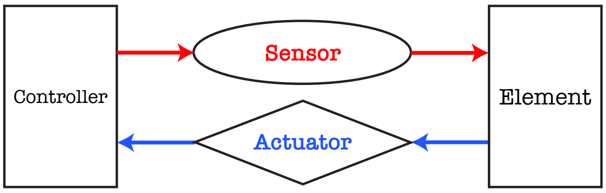

Figure 6: A representative diagram of a system using a sensor and actuator pair that operate in different modalities. The element is the physical assemblage being sensed and actuated while the controller is the digital, or electronic, subsystem.

Another common approach to simultaneous sensing and actuating within existing DMI designs is to utilise different modalities to sense and actuate, shown in Figure 6. When creating close couplings, these modalities and transduction methods may end up sensing and actuate similar physical properties (such as mechanical vibration). Sensing and actuating with different modalities can be a desirable option when aiming to avoid crosstalk between the two.

One example of this is the Electromagnetically Sustained Rhodes Piano. After initially creating a feedback sustain system using electromagnetic actuators and electromagnetic pickups, Shear and Wright [59] switch to instead using piezoelectric pickups for sensing. Though this differs from the normal sensing operation of a Rhodes electric piano (which uses electromagnetic pickups), the use of piezoelectric sensing prevented the signal from the electromagnetic actuator from directly coupling to the pickup.

Berdahl et al. [6] also uses a voice coil transducer with a piezoelectric sensor (collocated upon the actuator) for interaction and feedback with a virtual string waveguide model in their Cellomobo instrument design.

In another example from NIME literature, Schmidt et al. [58] use Lorentz force actuation alongside optical sensing to self-sustain harpsichord strings. Lorentz force actuation is used instead of electromagnetic actuation often seen with string actuation as the brass harpsichord strings are not ferromagnetic. This also means that electromagnetic pickups cannot be used for sensing the string. Optical sensors are used instead of piezoelectric pickups as they provide the isolation required to sense a single string. When using different modalities, the properties that are sensed and actuated must be considered. In the example of Schmidt et al. [58], the optical sensors measure the displacement of the string. They implemented a differentiator circuit to process the sensor data, as a velocity signal made the feedback control more efficient.

4 Sensors and Actuators: Practical Considerations

Across Section 3, techniques for achieving closely-coupled sensing and actuating have been presented. While the premise of each technique is simple, in reality each technique has particular constraints and affordances when applied to real systems. The selection of a particular technique must also take into consideration the particular sensors and actuators selected for the system, along with the type of DMI system that the closely-coupled sensing and actuation is being applied to. An overview of the practical considerations of transducer selection and appropriate applications for each technique can be found in Table 1.

4.1 Linearity

Models of systems involving sensors and actuators with a control loop often assume such devices to be perfectly linear. Of course, in practice, no sensor or actuator is completely linear, all will exhibit some form of non-linearities. The level of such linearities is often dependent on the signal level being dealt with, along with the type of transducer and the construction of the device. Linearity is of particular concern for frequency-band separation techniques and impedance techniques. In the case of frequency-band separation, the non-linearities may cause the actuation signal to interfere with the sensing frequency band, as found by Laput et al. [35]. For impedance-based approaches, the system performance will deteriorate if it is assumed to be a linear system when it is actually non-linear.

4.2 Self-Sensing or Separate Transducers

Another design decision for closely-coupled systems is whether separate sensors and actuators should be used, or whether to use a single transducer as a self-sensing actuator to perform both duties.

Self-sensing techniques are used in a wide range of domains from active acoustic absorption [10, 39], to touch sensitive displays using LEDs [31, 72], to simultaneous force sensing and vibrotactile output [19–21, 70].

While there are numerous justifications for implementing self-sensing, such as a reduction in components or mechanical constraints limiting the system to a single transducer, one of the most significant benefits is the perfect collocation of sensing and actuation afforded by it. This can simplify the control when closed-loop feedback is applied as the propagation delay between the two transducers does not need to be considered [5].

On the other hand, separate sensing and actuating transducers can enable performance benefits. Generally the design of transducers makes them suited to one purpose or the other. A voice coil loudspeaker, for example, can operate as a microphone but is inefficient at capturing high frequency sounds due to the mass of the coil and its inertia. In this example, separate transducers could likely produce a better performing system when operating at high frequencies.

4.3 Active Sensing: Actuating to Sense

A common approach to sensing (particularly when sensing passive systems) is to first actuate the system using some form of

Technique	Transducer Considerations	Application Considerations
Time-Division Multiplexing	Low-inertance actuators (such as Lorentz force string actuation) work better to avoid crosstalk	There is a trade-off between bandwidth and inertance; high frequency operation requires low-inertance transducers. Only suitable for situations where the actuation has sufficient headroom – the idle time between actuation pulses lowers the power output
Frequency-Band Separation	Actuator must be linear to avoid crosstalk into sensing band. Transducer(s) must have wideband operation to have enough usable bandwidth to segment in frequency domain.	Suitable for haptic interaction and sensing and combining multiple modes of sensing and actuation. Unsuitable for active control or resonant feedback.
Electrical Impedance	Not suited to non-linear transducers or systems with impedance characteristics that are difficult to model. Transducer must be efficient to reduce crosstalk from actuation to sensing. The resonance of a voice coil transducer determines its most efficient frequency range.	Suitable for vibrotactile haptic feedback and self-sensing active control (around resonance of transducer).
Mechanical Impedance	For force feedback haptics, choose actuator and sensor based on intended stiffness simulation (either impedance or admittance approach). For active control of mechanical vibrations, it is beneficial to collocate sensor and actuator.	Suitable for force feedback haptics (usually using separate sensor and actuator) or active control of mechanical vibration.
Acoustic Impedance	Sensor and actuator must be collocated (or distance accounted for in DSP). Transducers must behave close to linearly.	Suitable for active control of acoustics. Usually unsuitable for high-frequency control due to system latency.
Different Modalities	The attribute that the sensor is sensing must be considered (e.g. displacement/velocity/acceleration) as this may effect the control loop implementation.	Good for situations where crosstalk between transducers must be minimised.

Table 1: A summary of each approach for achieving closely-coupled sensing and actuation, with considerations around the transducer(s) used and suitable applications.

excitation signal, before sensing the response to the excitation signal. Through active excitation of the system being measured, further information can be gathered than through passive sensing alone.

While the actuation exists purely for the purposes of enabling the sensing to occur, the actuation system is often also used for actuating beyond the excitation signal required for sensing (using techniques described in this paper – such as frequency band separation – to separate the active sensing from the other actuation). Active sensing has been used in HCI applications with ultrasonic acoustic sensing used to detect gestures and changes in tangible interfaces [35, 36]. Similar swept frequency sensing approaches have also been deployed with capacitive sensing [56].

Within DMI design literature, active sensing has been used for sensing proximity while delivering mid-air haptics using ultrasonic transducers [16], to map parameters of a synthesiser based upon the change in resonant characteristics of a physical interface using a voice coil transducer to excite the system [37], and to sense the change in damping of a voice coil transducer when used for haptic feedback and vibration detection [19].

5 Ongoing Problems and Shortcomings

As proposed in Section 1, an ideal closely-coupled hybrid system should be capable of simultaneous transfer of energy between domains at a single physical point, with a wide bandwidth in both directions. This paper has presented techniques that, if selected and implemented with sufficient consideration, are able to achieve closely-coupled hybrid system in a specific use case. The usual approach of breaking one, or more, of the closely-coupled requirements in practice prompts the questions: where do current techniques fall short? What further technical development is required to achieve a 'perfectly' closely-coupled system? The lack of a method for closely-coupled sensing and actuation that works more generally naturally leads to consideration of where in the system the shortfalls currently exist.

A significant limitation in achieving this ideal behaviour is the latency of digital systems. To be sufficiently fast as to be able to exert control across the audible frequency requires sample-by-sample processing at roundtrip latency rates exceeding 40kHz [7]. While audio systems almost universally exceed the sample rate requirements of this, they often do so using sample buffers on the inputs and outputs in combination with converters that add additional latency, resulting in a roundtrip latency of near 1 millisecond for purpose-built embedded systems to multiple milliseconds for general purpose computing devices [49].

Additionally, the low efficiency that most transducers exhibit when transferring energy between domains is another limiting factor. This is a particular limit on self-sensing designs – where the electrical signal created by the actuation is likely to have a significantly larger magnitude than the signal induced through sensing. Crosstalk cancellation is therefore made more difficult due to the difference in magnitude. Further considerations are the linearity and bandwidth. Non-linearities in the transducers makes the system more difficult to model, and a finite operational bandwidth naturally limits the usable frequency range of the system.

Finally, the limited transient response of actuators can limit the achievable outcomes in DMI design. While not a problem specific to closely-coupled sensing and actuating (this remains an issue in designs where the actuator is supplied with an external signal), the considerations are important for closely-coupled systems. This is particularly noteworthy for actuation or self-sustaining of resonant instruments (such as the eBow and the Magnetic Resonator Piano [47]) which often perform best when actuating a continuous sustain with a slow attack. This is largely due to the limits of transducers – energy cannot be converted from the electrical to mechanical domain quickly enough to create a large transient. In hybrid instruments where large transients can be achieved, such as robotic instruments [40], energy is first converted from electrical to stored mechanical inertia and then released as a transient (such as a motor that moves a robotic beater to hit a drum).

With these limitations in mind, a generalised system for achieving closely-coupled sensing and actuation remains a challenge. The techniques presented in this paper, however, demonstrate that it is possible to create systems that achieve a suitable level of coupling when the constraints of the particular application are carefully considered.

6 Conclusion

Closely-coupled sensing and actuation is a necessary part of many hybrid physical-digital instrument designs. Achieving such a coupling, however, is not always straightforward – particularly at the bandwidths required for audio-rate interaction. This paper presented techniques that can be used to achieve such couplings. While examples of DMI designs have been covered, many of the examples and techniques discussed here are sourced from other research areas and remain under-explored in NIME. We hope that by discussing these within the context of DMI design, renewed interest is sparked in the possibilities of hybrid instruments using novel sensing and actuation methods.

7 Ethical Standards

This work is a review of technologies and techniques and involved no research participants.

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