Z-Wah: Appropriating the Wah via Digital Impedance Synthesis

Francisco Bernardo
f.bernardo@imperial.ac.uk
Dyson School of Design Engineering
Imperial College London
London, UK

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

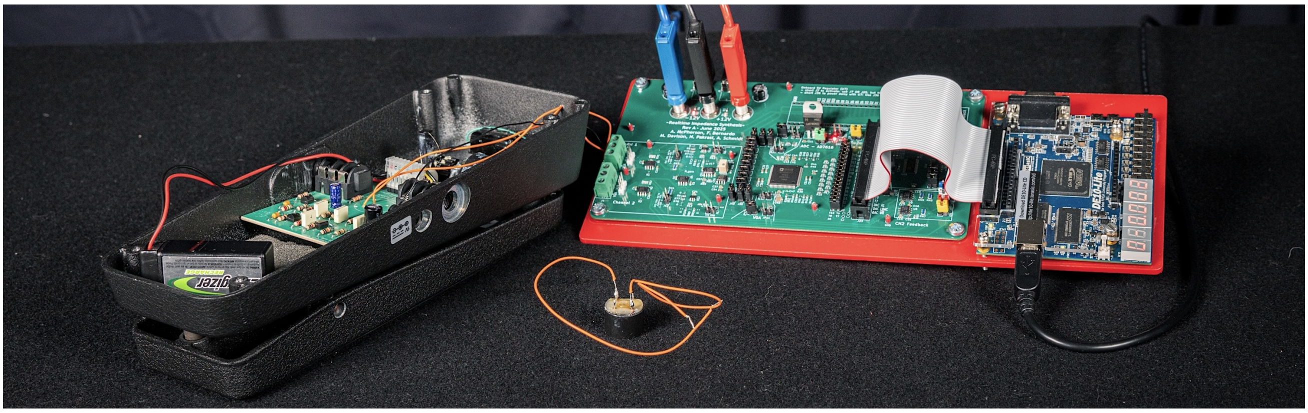

Figure 1: An augmented Dunlop Cry Baby wah pedal with its removed inductor, shown centre, replaced by a synthetic digital impedance implemented using a bespoke data-conversion PCB and an FPGA-based DSP processor, on the right.

Abstract

Digital impedance synthesis is a viable technique for appropriating and augmenting electronic musical instruments and effects. It enables in-circuit augmentation by replacing selected analog components with a low-latency embedded system that presents a programmable voltage-current relationship to the surrounding circuit. By defining the hybrid boundary between the analog and digital as an impedance relationship rather than a unidirectional control stream, the technique supports reciprocal coupling of subsystems, mutual influence, dynamic emergent interaction and complex behaviour. We demonstrate the approach with an augmented wah pedal that embeds a hybrid virtual-analog system which replaces key passive elements inside the resonant network, potentially allowing a continuum from close emulation to deliberate mismatch and instability as musical material. The contribution is a method for augmenting legacy electronic instruments from within their circuitry and expanding the space of repeatable and exploratory modifications, along with design implications for directionality, feedback, and the aesthetics of hybrid idiosyncrasy.

Keywords

Augmented instruments, appropriation, hacking, embedded hardware, virtual analog modelling, mapping

1 Introduction

Mass-produced electronic musical instruments and effects occupy a paradoxical role in musical culture. On one hand, they are standardized commodities: stable, repeatable, and designed to minimize unpredictability. On the other, they are widely appropriated musical technologies, routinely repurposed through repair, modding, and misuse. Some perspectives on appropriation suggest that this is not an anomaly but a normal outcome of technologies being deployed in the world, and that designers can support appropriation by making systems more transparent, reconfigurable, and open to reinterpretation rather than enforcing a single intended mode of use [5, 6, 29]. In musical contexts, this implies that instrument design does not end at manufacture; it continues through communities of practice that discover, circulate, and stabilize new uses.

On the other hand, typical approaches to digital augmentation of analog or acoustic systems place computation at the boundaries of the device, using external controllers with control voltages or digital potentiometers or replacing their circuits entirely by end-to-end digital signal processing (DSP) chains. This often preserves the enclosure and interface while shifting expressive control to unidirectional mappings between signals and parameters. Approaches based on modularity and directionality have a long technical and cultural history [26], but they can overemphasize one-way relationships and stable parameter spaces [19], masking or removing the reciprocal coupling, circular causality, and fast-time-scale interactions through which many instruments acquire their playable character.

If the expressive identity of electronic instruments emerge from reciprocal internal relations—loading, resonance, feedback, and non-ideal component behaviour—then augmentation that operates only at the level of parameter mapping risks bypassing precisely what makes the instrument musically distinctive. A key question for augmenting mass-produced electronics is not only how to preserve stability and repeatability, but also how to open access to the device's internal dynamical possibilities [18], so that messiness, mismatch, and feedback can be harnessed for artistic ends, rather than discarded or wasted as error.

NIME '26, June 23–26, 2026, London, UK

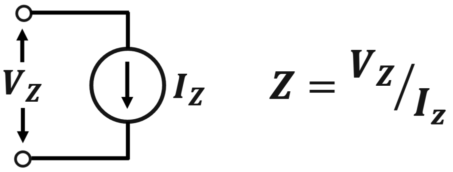

Figure 2: *Synthetic impedance and the impedance relation.*

This paper argues for digital impedance synthesis as an alternative technique for appropriating and augmenting mass-produced electronic instruments. In digital impedance synthesis, a programmable two-terminal element is embedded within an existing analog circuit so that, at a chosen node, it presents a target impedance *Z(s)*—or admittance *Y(s)*—by sensing voltage and producing the corresponding current in real time [1]. Implemented as a voltage-controlled current source (VCCS) with digital signal processing in the loop, the element replaces a selected physical component with its virtual counterpart and interacts bidirectionally with the surrounding circuit. By defining the hybrid boundary as an impedance relation (voltage/current) rather than a control stream, the approach preserves reciprocal coupling and allows augmentation to operate at the level of the circuit’s own causal structure.

In a NIME context, this aligns with the view that expressivity is shaped by constraints and internal material dynamics, and that design benefits from making those dynamics reachable rather than hidden [18]. It also resonates with research on hackable instruments that foregrounds exposed scaffolding and hardware–software feedback as enablers of appropriation [20, 29]. Relocating the editable locus from external control layers (interfaces and mappings) to internal impedance relations expands the expressive surface of mass-produced devices, enabling repeatable modification, parametric exploration, and intentional hybrid mismatch without abandoning a culturally legible interface.

We demonstrate the technique through a case study repurposing a stock wah pedal by embedding a low-latency virtual-analog subsystem within its resonant network and replacing a key passive element with a synthetic impedance. While the artifact provides a concrete testbed, the main contribution of this paper is the technique itself and its design implications for impedance boundary placement, latency, stability, and the aesthetic trade-off between accurate emulation and productive idiosyncrasy. The remainder of the paper reviews related work, describes the implementation, and discusses boundary placement as a musical interface design parameter rather than an engineering afterthought.

2 Background work

2.1 Circuit bending, *mods* and appropriation

Circuit bending treats mass-produced electronics as an *immediate canvas*: rather than starting from a design hypothesis, practitioners probe circuits directly and iteratively, privileging accidental discovery and an “anti-theory” ethos in which explanation follows (if at all) from hands-on exploration [11]. In this view, modification is not merely repair or optimisation but a creative act that re-authors what a device *is*, often by pushing it into unstable or unintended regimes. This aligns with research on hackability and appropriation in digital musical instruments [29], where modification is framed as a legitimate extension of design rather than a deviation. Hackability extends customisation into *redefinition*: instruments are shaped so users can adapt the technology to emerging musical purposes. Appropriation does not require explicit customisability—constrained tools can still be used idiosyncratically [15]—but design choices condition how likely and shareable such redefinitions become.

Appropriation is also mediated less by what a system offers than by what it limits. Constraints may be initially opaque and become apparent only through sustained engagement; “getting a feeling” for the boundaries of a system can be more reliable than reasoning from surface affordances [18]. This suggests that appropriation is facilitated when the seams of an instrument are reachable: when internal structures can be rewired or perturbed and meaningful change is not confined to a top-level interface. Approaches that expose internal scaffolding and support hardware–software feedback loops aim to make instruments robust to intervention, so that outcomes can emerge through disruption rather than being exhaustively specified in advance [20].

Finally, dimensionality complicates the assumption that more control necessarily yields more expressivity. Adding control dimensions can reduce exploration when new parameters become dominant constraints, drawing attention toward a single perceived limitation and away from hidden affordances [30]. This implies a practical cognitive bandwidth for appropriation: beyond some point, additional degrees of freedom can narrow (not expand) the space that performers actually explore and come to “own.” In this context, reductionist interfaces which restrict apparent degrees of freedom, can be more effective at redirecting attention from “precision setting” toward exploration, embodied negotiation, and collective performance practice [3].

2.2 Virtual analog modelling and bending

Virtual analog (VA) modelling elevates audio circuit models from analytical and descriptive tools to executable dynamical systems. Voltages and currents are expressed as coupled equations whose internal variables correspond to circuit behaviour, enabling “white-box” emulations of pedals and other analog devices [14]. In real time VA model execution, two constraints dominate: a) nonlinear elements must be solved fast enough for audio-rate operation (often requiring iterative solvers or explicit analytical equations), and b) the numerical scheme must remain stable across inputs and settings.

There are different VA formalisms, each with its own set of tradeoffs. State-space and nodal-analysis approaches derive nonlinear difference equations from circuit structure, with discretisation choices shaping both accuracy and cost [14]. Wave-based approaches such as Wave Digital Filters (WDF) reformulate Kirchhoff variables into incident/reflected waves, yielding structured implementations where stability depends on port-resistance choices, element adaptation, and handling of delay-free loops [12].

Interestingly, VA models can also function as a design platform. Model bending extends circuit-bending sensibilities to executable models: the model becomes an “‘immediate canvas”’ [11] for intervention and exploration rather than a fixed target for validation [13]. Models afford transformations that hardware cannot, and different formalisms expose different “handles” (e.g., port impedances, nonlinear definitions, discretisation artefacts), so accuracy becomes a choice rather than a default [13]. This opens a productive tension between close emulation and the deliberate cultivation of mismatch as an aesthetic and instrumental resource.

2.3 Reciprocal coupling via impedance synthesis

In much DMI design, *mapping* is treated as a chain: sensors produce signals, a mapping layer converts them into parameters, and a sound engine renders the result [28]. This is useful, but it can also make interaction look more orderly than it is. It encourages relationships to be treated as fixed functions between parameter spaces and can lead to *reification*, where named musical qualities are treated as if they were stable controllable objects [19]. Mapping tools also bias what is easy to express (often linear, low-dimensional relations), subtly steering instrument aesthetics [18, 30].

Many instruments do not behave like one-way chains (e.g. Peter Blasser's synthetizers [2]). With feedback, causes and effects loop back: the system becomes stateful, small changes can trigger qualitative shifts, and outcomes depend on where the system currently is. Hardware–software feedback makes this explicit [1, 20]: signals produced in software are transformed by an analog network, return through the ADC, and shape what software produces next, often operating near the boundary between stable and self-excited behaviour. This suggests treating the analog–digital boundary as a design choice rather than a fixed division.

Digital impedance synthesis follows this approach by defining the connection as a reciprocal electrical relation rather than a control stream. A programmable two-terminal element is embedded in the circuit so that it behaves as a chosen impedance (or admittance), responding to the circuit's voltage by producing the corresponding current in real time [1]. This shifts the design question from "how do we map signals into parameters?" to "what kind of coupling do we want at this boundary?" while supporting appropriation through reconfiguration, pluggability, and user-defined intervention [6].

2.4 Messiness and unpredictability in non-linear dynamical systems and feedback musicianship

Musicians often value electronic instruments whose behaviour is not fully captured by stable parameter settings. Their responses can be stateful and partly unpredictable, such that interaction becomes navigation through regimes rather than precision control of variables. Work on nonlinear dynamics in musical interaction describes how performers develop technique by working near critical transitions, cultivating "edge" behaviours and returning to metastable regions instead of aiming for repeatable one-to-one mappings [23]. Feedback-based practices such as no-input mixing similarly treat circular causality as a musical resource, foregrounding entangled agency and "usefully complicated" behaviours that resist reduction to independent knobs [22]. More generally, dynamical approaches to interaction design argue that uncertainty can be authored, and that unpredictability need not be arbitrary noise, but can arise from structured dynamics whose patterns become learnable through practice [21].

Rather than producing randomness, nonlinear feedback systems often yield rich but repeatable behaviours that can be cultivated as technique [8]. In studies of improvising musicians interacting with dynamical instruments, two complementary modes recur: 1) edge-like interaction, where performers hover near bifurcation points to trigger shifts of discontinuity; and 2) deep exploration, where subtle variations within a narrow region build up to reveal extensive sonic nuance over time [23]. This literature motivates treating "messiness" as part of the expressive surface of electronic instruments—not a failure of control, but a source of discoverable pathways that can be stabilised and performed.

3 Case Study: Augmenting the Wah pedal

We present *Z-Wah*, an augmented stock Dunlop Crybaby Wah GCB-95 pedal [7]. Prior research shows that constrained interaction can foster discovery of "hidden affordances" [10], and that reductionist interfaces can redirect attention from "precision setting" toward exploration, embodied negotiation, and collective performance practice [3]. Also, that instruments can be designed—or redesigned—to support appropriation and modification [29]. We treat the GCB95 stock wah as an appropriable instrument platform and integrate low-latency embedded computation directly into the analog circuit. Digital impedance synthesis turns a stock wah into a hybrid canvas: it can be tuned toward emulation of the original component, or pushed toward intentionally nonphysical impedances and productive mismatches that foreground the hybrid system's idiosyncrasies. By embedding computation inside the wah's resonant network, to selected passive components—most notably the inductor—using digital impedance synthesis, we preserve the canonical one-degree-of-freedom treadle interaction while opening a programmable locus for iterative experimentation, extension, and re-voicing.

3.1 The Wah Pedal as socio-technical artifact and modding substrate

Wah pedals are iconic expressive devices: a single continuous foot gesture controls a resonant sweep whose musical identity depends not only on frequency response but also on how the pedal loads, and is loaded by, the surrounding analog signal chain. The wah's lineage has a long arc of re-issues and copies that became commercially dominant partly because the original Vox/Thomas Organ designs were widely cloned and reinterpreted [27]. Models such as the Vox 847 or the Dunlop Cry Baby GCB95 sit in a peculiar position: they are simultaneously industrially standardised mass products but also "open secrets" of folk engineering, continuously reverse-engineered, narrated, and re-authored by builders and players.

Another relevant layer of meaning comes from why wah sounds like human voice. Keen's "Human Voices and the Wah Pedal" analysis [16] ties the vocal analogy to vowel formants: the first formant region for an "ah" vowel (roughly 700–1200 Hz) aligns closely with the sweep region of the canonical wah resonance, but a standard wah provides only one resonant peak, leaving out the second formant that contributes strongly to vowel identity. This explains both the recognisable vocality and the perceptual limit: wah evokes speech without fully specifying it. This socio-technical condition matters for NIME: the Wah is not just a pedal or circuit, but a stable cultural interface whose "correctness" is negotiated through communities of modification and boutique re-tuning.

These two frames motivate a hybrid intervention: preserve the embodied, performative interface of the wah while opening its "voice model" and its circuit parameters to a broader design space.

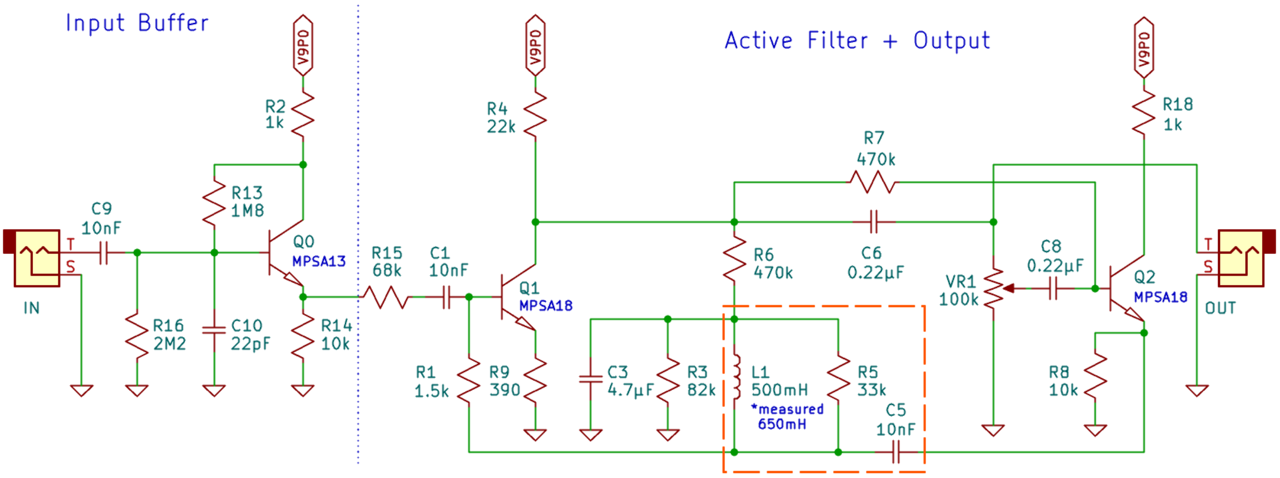

Figure 3: *Dunlop GCB95 wah circuit schematic, based on [9] but relabelled according to the 2003 Rev. H and 2007 Rev. I circuit versions. The schematic shows the input buffer and active filter/output stages, with the orange dashed outline highlighting the RLC resonant filter network centred on L1, R5 and C5, which determine the filter response.*

3.2 Structural analysis of the stock Dunlop Crybaby Wah GCB95 circuit

The Dunlop GCB95 comprises several functional blocks, including an input buffer, the resonant filter stage (Figure 3), and an output stage. The resonant filter stage, the core of the wah, is not a simple filter with a knob. It is an active, impedance-coupled resonance. The canonical Crybaby/Vox mechanism can be understood as an LC resonance whose apparent capacitance is electronically varied by the transistor stage and the wah pot [17]. The first transistor is a block of gain that provides an active resonance. The wah pot, the second transistor and the fixed capacitor implement effectively an electronically-variable capacitance. Together with the fixed inductor, they form a resonant circuit. The variable capacitance of the circuit and interacts with the inductor to form the adjustable LC filter that causes the wah effect.

The overall response can be described as a low-pass filter with a resonant peak, rather than a pure narrow band-pass. This explains the characteristic vowel formant-like sweep [16]. Two details from the circuit are especially relevant:

(1) The inductor (L1, 500mH) has measurable differences in harmonic behaviour under drive, including asymmetric saturation effects [17].
(2) The parallel resistor (R5, 33k) to the inductor governs the Quality (Q) factor, the main determinant of resonance sharpness—lower values soften the effect and higher values increase peak resonance.

An intervention on these elements via digital impedance synthesis is not merely about replacing the elements at the level of nominal impedances but also at the non-idealities (and cultural expectations).

3.3 Prior modifications of the GCB95

The modding culture around the GCB95 is extraordinarily rich, ranging from simple component modifications and circuit extensions, to circuit replacement kits, to fully modded pedals available on the market. The "mod" literature effectively acts like an informal parameter map of the wah's perceptual space. A few notorious online sources have compiled and analysed some of the most import mods, which we list next for reference:

(1) Q / “Vocal” mod – a widely-circulated modification is changing the resistance value of the resistor (R5) in parallel with the inductor, explicitly to change the filter's Q (resonance sharpness), often cited as improving perceived vocality.
(2) Sweep-range mod (changing the core sweep capacitor) ElectroSmash [9] describes a sweep mod achieved by replacing the sweep capacitor (C5 in Figure 3), with suggested values that shift the sweep downward for bass or “Hendrix” voicings. Stinkfoot [24] similarly lists using 0.015 μF or 0.022 μF to lower the range, and notes 0.068 μF as a bass-oriented extreme.
(3) Resonance peak position / mids shaping small resistor changes shift the resonant peak character [24]. Bias and gain-setting resistors can push transistor stages toward saturation, changing tone and sometimes introducing distortion—i.e., “tuning” often drifts into nonlinear behaviour [17].
(4) Bypass / buffering and the historical “tone sucking” problem: older SPDT switching leaves the circuit loading the guitar even when bypassed—two canonical cures—true bypass switching or adding a buffer ahead of the wah.

The GCB95 already lives in a culture where parameterisation is expected—our contribution is a new technical means that operates at the impedance level rather than through potentiometers and component swaps.

3.4 Our implementation

Our approach inserts a digitally controlled impedance element into the GCB95 circuit. This way, the pedal remains an electrical system whose behaviour emerges from interaction between analog and digital subsystems. Figure 4 shows a schematic of the synthetic impedance element, implemented as a VCCS. We use high-speed data converters, a 16-bit SAR ADC and a 16-bit DAC, and an Altera DE10-Lite FPGA (centre of the circuit) to implement an ultra-low-latency digital signal processor. The behaviour of this circuit depends on the output voltage V_{out} and resistor R_{out} (Eq. 1, Figure 4).

Our implementation is applicable both as a ground-referenced or floating synthetic impedance. In the first case, the application

$$I = (V - V_{out})/R_{\mathrm{out}} \tag{1}$$

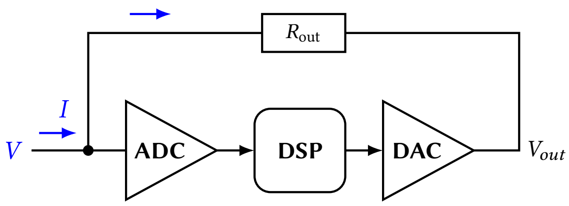

Figure 4: *Digital synthetic impedance implemented as a voltage-controlled current source (VCCS) [1].*

assumes one of the two terminals of the synthetic impedance is connected to ground. In the later case, it uses a differential input stage and a second output to allow for simulation of floating impedance elements.

The DE10-Lite FPGA fabric is configured to implement an unbuffered, single-sample DSP system running at 706 kHz, yielding an end-to-end latency of approximately 2 us. Anti-aliasing is provided by the ADC's on-board first-order Butterworth low-pass filter with a 39 kHz corner frequency. Signals are represented in fixed-point Q5.11 format, using volts as units over a nominal ±10 V range. The system implements a discrete-time approximation of an admittance $Y(s) = I(s)/V(s)$. For linear elements, Y(s) is realised as an IIR filter obtained by applying a prewarped bilinear transform to the corresponding continuous-time impedance/admittance model. Given a discrete-time current $i_{in}[n]$ corresponding to Equation (1) (Figure 4), the signal to the DAC (in volts) is calculated as:

$$v_{DAC}[n] = -\mathrm{R}_{\mathrm{out}} i[n]. \tag{2}$$

The signal $\mathrm{v}_{\mathrm{DAC}}[\mathrm{n}]$ is then renormalised from a ±10 V range to the full output range of the DAC (0-65536 for a 16-bit DAC).

3.5 Evaluation

To probe how digital impedance synthesis alters the behaviour of the stock Dunlop GCB95, we conducted a set of exploratory tests in which a synthesized impedance element was inserted at different points in the circuit. The tests were designed to contrast grounded versus floating couplings, and to compare synthesis of a resistor and an inductor. The aim was to observe shifts in interaction regime—from recognizable filtering to noise/instability and self-oscillation—rather than to measure fidelity.

3.5.1 Configuration 1: Virtual resistor as grounded impedance on resonant node. A synthesized resistor shunt to virtual ground was inserted at the inductor L1 terminals. (a) Some virtual resistance settings produced continuous noise/squeals while the wah pot still operated; in certain cases the synthesized element dominated and partially overrode the guitar input. (b) Swapping to the opposite inductor terminal changed behaviour; setting one specific resistor value recovered a stable guitar signal and yielded effects such as damped resonance, bass emphasis, mid-hum noise.

3.5.2 Configuration 2: Virtual resistor as floating impedance across L1 (inductor retained). A synthesized floating resistor was placed across the inductor without removing it. The guitar input was often suppressed, yielding "no-input" material—glitches, squeaks, chirps, and intermittent tones—all steerable with the wah pot. After the guitar input was removed, the pedal behaved effectively as a "no-input" wah, producing the same kinds of content.

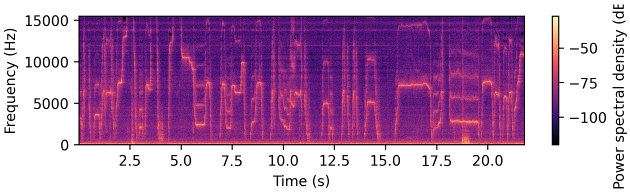

Figure 5: *Configuration 1 audio recording spectrogram.*

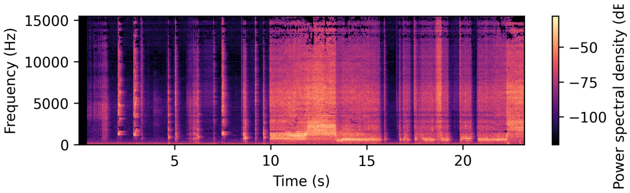

Figure 6: *Configuration 2 audio recording spectrogram.*

3.5.3 Configuration 3: Virtual inductor as floating impedance replacing the inductor. A synthesized inductor replaced the stock inductor as a floating element in the resonant network. This produced the richest outcomes: highly distorted bass, sawtooth-like waveforms, very low-frequency oscillations, rhythmic drones, and ring-oscillation-like behaviour, all navigable with the wah pot. Using an ADC-controlled pot to set a DC operating point while admitting guitar input enabled additional perturbation and modulation, blending external excitation with internally generated dynamics.

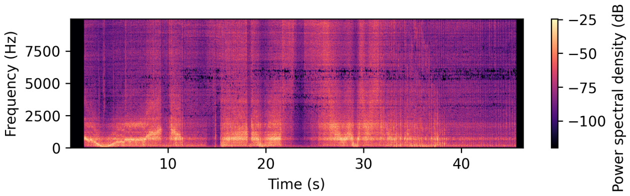

Figure 7: *Configuration 3 audio recording spectrogram.*

4 Discussion

4.1 Directionality and feedback

The Z-Wah serves as a case study in what DMI design might look like without directional, modular units connected in well-defined mappings [19]. There is no "input" or "output" in an electrical impedance element, only a relationship between voltage and current, which in this case is programmable. (Technically, in the FPGA, current is calculated as a function of voltage with a unit delay. However, voltage reciprocally depends on current, frustrating any attempt to understand it as a directional mapping.) Like most feedback systems [25], the behaviour of any given element emerges as an entangled property of all elements of the system. Thus, in both technology and in effect, impedance synthesis in this context acts as a kind of drop-in feedback source for analog circuits.

Our case study did incorporate one aspect of classical mapping techniques, namely the auxiliary ADC input which manipulated the value of the synthetic inductor and resistor. We configured this with a potentiometer to set the DC operating level with the guitar signal added as an AC offset, such that the value of the simulated component changed at audio rates alongside the guitar signal, changing the character of the feedback. Generalising from this case study, a possible use of the auxiliary ADC inputs is to provide a bridge between the directional world of mapping and signal processing systems, and the entangled and emergent behaviours of real or synthetic analog circuits.

4.2 Augmented circuit bending, bent augmentations

Synthetic impedance offers the potential to traverse a space of possibilities, between standard operation, implemented as a controlled modification of a circuit by precisely simulating conventional components, or unstable, chaotic behaviour, leveraged by the exploratory disruption of the circuit topology. The former is conceptually in line with the guitar pedal "mod" literature, the latter with circuit bending and hardware hacking [5, 11]. We have chosen the latter approach in our case study.

Like circuit bending, our approach is 'anti-theoretical' [11] and phenomenological (we cannot necessarily know or predict how a modification will work) and the results embrace a noisy glitch aesthetic [4]. But synthetic impedance can go a step further than a typical circuit bend: rather than creating short circuits or open circuits, we can create arbitrary voltage-current relationships, including inherently unstable ones that destabilise the host circuit, as in the Z-Wah. Synthetic impedance could thus be developed as a kind of augmented circuit bending tool.

On the flip side, the Z-Wah represents an appropriation or creative misuse not only of the wah pedal, but of the synthetic impedance jig itself, which was originally designed for controlled simulations [1]. The behaviour of the Z-Wah involves high-frequency instabilities within the synthetic impedance system, which are nominally failure modes of the system: it is not meaningfully simulating an analog inductor when it goes into high-frequency oscillation, even if the behaviour is interesting on its own terms. Thus we might consider the Z-Wah to be a bent augmentation: a notionally augmentative technology turned on its head.

5 Ethical Standards

This work is an empirical study of a technical system and involved no research participants.

Acknowledgments

This research was supported by a UKRI Frontier Research (Consolidator) grant EP/X023478/1 (RUDIMENTS) and by the Royal Academy of Engineering under the Research Chairs and Senior Research Fellowships scheme.

References

[1] Francisco Bernardo, Matthew Davison, and Andrew McPherson. 2025. Impedance Synthesis for Hybrid Analog-Digital Audio Effects. In *Proceedings of the 28th International Conference on Digital Audio Effects (DAFx-25), Ancona, Italy.*

[2] Peter Blasser. 2015. *Stores at the Mall.* Master of Arts Dissertation. Wesleyan University, Middletown, CT. https://doi.org/10.14418/wes01.2.84

[3] John Bowers, John Richards, Tim Shaw, Jim Frize, Ben Freeth, Sam Topley, Neal Spowage, Steve Jones, Amit Patel, Li Rui, and Will Edmondes. 2016. One Knob To Rule Them All: Reductionist Interfaces for Expansionist Research. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME 2016).* 43–49. https://doi.org/10.5281/zenodo.1175996

[4] Kim Cascone. 2000. The Aesthetics of Failure:"Post-Digital" Tendencies in Contemporary Computer Music. *Computer Music Journal* 24, 4 (2000), 12–18. https://doi.org/10.1162/014892600559489

[5] Nicolas Collins. 2009. *Handmade Electronic Music: The Art of Hardware Hacking* (3rd ed.). Routledge.

[6] Alan Dix. 2007. Designing for appropriation. In *Proceedings of the 21st British HCI Group Annual Conference on People and Computers: HCI...but not as we know it - Volume 2 (BCS-HCI '07).* BCS Learning & Development Ltd., Swindon, GBR, 27–30. https://dl.acm.org/doi/10.5555/1531407.1531415

[7] Dunlop. [n. d.]. GCB95 Original Cry Baby. https://www.jimdunlop.com/content/manuals/GCB95.pdf Accessed on April 30, 2026.

[8] Alice Eldridge, Chris Kiefer, Dan Overholt, and Halldor Ulfarsson. 2021. Self-resonating Vibrotactile Feedback Instruments ||: Making, Playing, Conceptualising :||. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME 2021).* https://doi.org/10.21428/92fbeb44.1f29a09e

[9] Electrosmash. 2013. Dunlop Crybaby GCB-95 Circuit Analysis. https://www.electrosmash.com/crybaby-gcb-95 – Accessed on April 30, 2026.

[10] William W. Gaver. 1991. Technology affordances. In *Proceedings of the SIGCHI conference on Human factors in computing systems Reaching through technology - CHI '91.* ACM Press, New Orleans, Louisiana, United States, 79–84. https://doi.org/10.1145/108844.108856

[11] Reed Ghazala. 2005. *Circuit-Bending: Build Your Own Alien Instruments.* Wiley Pub, Indianapolis, IN.

[12] Riccardo Giampiccolo, Sebastian Cristian Gafencu, and Alberto Bernardini. 2025. Explicit Modeling of Audio Circuits with Multiple Nonlinearities for Virtual Analog Applications. *IEEE Open Journal of Signal Processing* (2025), 1–9. https://doi.org/10.1109/OJSP.2025.3528334

[13] Daniel J Gillespie and Samuel Schachter. 2022. Model Bending: Teaching Circuit Models New Tricks. In *Proceedings of the 25th International Conference on Digital Audio Effects (DAFx20in22) Vienna, Austria.*

[14] Chet Gnegy and Kurt James Werner. 2015. Digitizing the Ibanez Weeping Demon Wah Pedal. In *Proc. of the 18th Int. Conference on Digital Audio Effects (DAFx-15), Trondheim, Norway.*

[15] Michael Gurevich, Paul Stapleton, and Adnan Marquez-Borbon. 2010. Style and Constraint in Electronic Musical Instruments. In *Proceedings of the International Conference on New Interfaces for Musical Expression, Sydney, Australia.* 106–111. https://doi.org/10.5281/zenodo.1177785

[16] R.G. Keen. 1999. Human Voices and the Wah Pedal. http://geofex.com/Article_Folders/wahpedl/voicewah.htm – Accessed on April 30, 2026.

[17] R.G. Keen. 1999. The Technology of Wah Pedals. http://geofex.com/Article_Folders/wahpedl/wahped.htm – Accessed on April 30, 2026.

[18] Thor Magnusson. 2010. Designing Constraints: Composing and Performing with Digital Musical Systems. *Computer Music Journal* 34, 4 (Dec. 2010), 62–73. https://doi.org/10.1162/COMJ_a_00026

[19] Andrew McPherson, Landon Morrison, Matthew Davison, and Marcelo M. Wanderley. 2025. On Mapping as a Technoscientific Practice in Digital Musical Instruments. *Journal of New Music Research* (Jan. 2025), 1–16. https://doi.org/10.1080/09298215.2024.2442356

[20] Andrew P McPherson and Victor Zappi. 2015. Exposing the Scaffolding of Digital Instruments with Hardware-Software Feedback Loops. In *Proc. New Interfaces for Musical Expression, Baton Rouge, LA, USA.* https://doi.org/10.5281/zenodo.1179134

[21] Tom Mudd. 2023. Playing with Feedback: Unpredictability, Immediacy, and Entangled Agency in the No-input Mixing Desk. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems.* ACM, Hamburg Germany, 1–11. https://doi.org/10.1145/3544548.3580662

[22] Tom Mudd and Akira Brown. 2023. Musical pathways through the no-input mixer. In *Proceedings of the International Conference on New Interfaces for Musical Expression, Mexico City, Mexico, 402–408.* https://doi.org/10.5281/zenodo.11189224

[23] Tom Mudd, Simon Holland, and Paul Mulholland. 2019. The Role of Nonlinear Dynamics in Musicians' Interactions with Digital and Acoustic Musical Instruments. *Computer Music Journal* 43, 4 (Dec. 2019), 25–40. https://doi.org/10.1162/comj_a_00535

[24] Andreas Möller. 2010. Changing the tone of the GCB-95 Crybaby. https://stinkfoot.se/archives/549 – Accessed on April 30, 2026.

[25] Dario Sanfilippo and Andrea Valle. 2013. Feedback Systems: An Analytical Framework. *Computer Music Journal* 37, 2 (2013), 12–27. https://doi.org/DOI:10.1162/COMJ_a_00176

[26] Ezra J Teboul. 2024. Preface (All Patched Up: A Material and Discursive History of Modularity and Control Voltages) . In *Modular Synthesis: Patching Machines and People.* Focal Press, 18–48.

[27] Art Thompson. 1992. Wah: The Pedal That Wouldn't Die. *Guitar Magazine* 26, 5 (1992), 58–64.

[28] Marcelo M Wanderley and Philippe Depalle. 2004. Gestural control of sound synthesis. *Proc. IEEE* 92, 4 (2004), 632–644. https://doi.org/10.1109/JPROC.2004.825882

[29] Victor Zappi and Andrew McPherson. 2018. Hackable Instruments: Supporting Appropriation and Modification in Digital Musical Interaction. *Frontiers in ICT* 5 (Oct. 2018), 26. https://doi.org/10.3389/fict.2018.00026

[30] Victor Zappi and Andrew P McPherson. 2014. Dimensionality and Appropriation in Digital Musical Instrument Design. In *Proc. New Interfaces for Musical Expression, London, UK, 2014.* 455–460. https://doi.org/10.5281/zenodo.1178993