Designing and evaluating an actively controlled acoustic guitar

Master Thesis

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Title:
Designing and evaluating an actively controlled acoustic guitar

Project Period:
Summer semester 2025

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Date of Completion:
May 25, 2025

Abstract:

This thesis investigates the design and evaluation of an actively controlled acoustic guitar, combining control theory with performer-centered design. Using current-sensing amplifiers and collocated actuation, a feedback system is developed to selectively damp structural modes in the guitar body. Experimental validation shows measurable attenuation of resonances. To explore expressive and perceptual effects, two interactive design probes were created, embedding audio effects into the feedback loop. These were evaluated through user studies with guitarists, using interviews to examine themes like control intimacy, expressive potential, and performer-instrument relationship. Results suggest that while sensing limitations remain, the system enables novel expressive affordances and reconfigures traditional instrument behavior. This work contributes to New Interfaces for Musical Expression (NIME) by connecting technical innovation with embodied musical interaction and points to future directions in augmented acoustic instruments.

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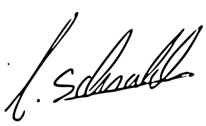
Preface

Aalborg University May 25, 2025



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Chapter 1

Introduction

1.1 Motivation and Background

This thesis is situated at the intersection of control theory, musical expression, and the design of augmented instruments. It was motivated, in part, by a recent technical development: the concept of a self-sensing transducer for tactile interaction, as proposed by Davison et al. [1]. This architecture enables simultaneous actuation and sensing using a single transducer, fulfilling the strict collocation requirements often associated with active control systems. Its potential as a foundation for low-latency, physically integrated feedback control appeared especially promising in the context of acoustic musical instruments.

At the same time, this work is informed by the long-standing tradition of guitar augmentation. The electric guitar itself can be viewed as an early and enduring example of instrument augmentation, where added amplification, effects, and hardware modifications have become intrinsic to musical practice rather than disruptive to it [2]. Unlike many actuated or digitally fabricated instruments explored within the NIME (New Interfaces for Musical Expression) community, which often emphasize novel forms of interaction, most work on active control has remained rooted in existing acoustic instruments, with a primary focus on technical validation. Prior research in this area has demonstrated the feasibility of controlling vibration modes or shaping acoustic responses through active systems, but has rarely extended into perceptual or experiential evaluation. This thesis differentiates itself by combining active control implementation with a design methodology that focuses on the performer's perspective. In doing so, it aims to bridge the gap between foundational control research and the rich tradition of performer-focused evaluation more commonly associated with other types of actuated instruments.

The project aligns with broader themes in NIME research, particularly those concerning control intimacy, expressivity, and embodied interaction. These themes are notoriously difficult to evaluate with conventional metrics. As such, the work also explores a design

methodology, cultural probes, that invites open-ended, subjective engagement from musicians, emphasizing discovery and interpretation.
This dual motivation, leveraging a novel control architecture and exploring changes in musical expression through familiar instruments, frames the technical and design goals of this thesis.

1.2 Research Gap

Although active acoustics for musical instruments has been explored since 1995 [3], it remains relatively underrepresented in the NIME community and in the broader field of musical instrument research. Most work in this area has centered on foundational technical challenges, such as vibration control, modal damping [4], and feedback stability [5], without deeply extending into the perceptual or experiential implications of such technologies in musical contexts.
Existing implementations of active control systems for musical instruments typically serve as proofs of concept, validating control objectives like damping or sustain. However, they rarely test how these interventions affect the performer's expressive interaction with the instrument. At the same time, research on actuated instruments more broadly has often emphasized performer experience and sonic experimentation, but generally without the control precision afforded by active control systems.
This gap is further compounded by practical barriers: active control systems are technically demanding to design and implement, often requiring custom electronics, low-latency processing, and careful sensor-actuator integration. These challenges may explain the limited application of active control in widely distributed or user-facing musical instruments.
In this context, the present work aims to bridge the gap between technically validated active control systems and the performer-centered methodologies that have proven effective in evaluating actuated instruments.

1.3 Research objectives and questions

The thesis addresses the following objectives:

1. To evaluate the feasibility of using current-sensing amplifiers and collocated actuation for active vibrational control in guitars.
2. To investigate how active control technologies affect the embodied and expressive relationship between the guitarist and the instrument.

This gives rise to the following research questions:

- What are the technical and perceptual limits of self-sensing control systems for guitar vibration?

- How do musicians perceive and adapt to disruption in their instrument's behavior introduced through active control?

1.4 Methodological Approach

The methodology employed in this thesis is twofold: technical validation and perceptual evaluation.
The first strand focuses on the experimental validation of a custom-built active control system. A series of controlled experiments was conducted to evaluate the system's ability to damp specific vibrational modes of an acoustic guitar body. These measurements, including impulse response analysis and decay time estimation, provided insight into the technical feasibility and performance of the proposed control setup.
The second strand adopts a more exploratory and experiential approach, drawing on the concept of cultural probes. Two interactive design probes were developed to examine how active control might disrupt or reshape the performer's relationship with the instrument. These probes incorporated different feedback mechanisms, one physically inspired, the other operating in the frequency domain, and were evaluated through individual sessions with guitarists. Semi-structured interviews were used to capture participants' subjective impressions, focusing on expressivity, control, and collaboration.

1.5 Thesis Structure

This thesis is organized into six chapters:

- **Chapter 2** introduces the theoretical framework, including background on augmented and actuated instruments, control theory relevant to active acoustics, and design principles for expressive musical interaction.
- **Chapter 3** details the implementation of the control system, including hardware design, actuator placement, and digital signal processing strategies used to achieve modal damping.
- **Chapter 4** presents the experimental validation of the control system, focusing on the system's ability to attenuate structural modes and sense string vibrations.
- **Chapter 5** introduces two interactive design probes that extend the system into musically expressive contexts and describes their conceptual and technical basis.
- **Chapter 6** evaluates the probes through semi-structured interviews with guitarists, identifying themes related to control, disruption, and co-performativity.
- **Chapter 7** concludes the thesis by summarizing its contributions, discussing limitations, and outlining future research directions.

Chapter 2

Theoretical framework

The research context of this thesis spans various fields rooted in control theory, design, and evaluation of musical instruments. This chapter first introduces current developments in augmented, actuated, and smart instruments, followed by foundational control theory relevant to their actuation, and concludes with design and evaluation frameworks for musical interaction.

2.1 Augmented Instruments

The terminology surrounding augmented, actuated, and smart instruments, particularly in the context of active control, is often used inconsistently across the literature. For the purposes of this thesis, it is therefore important to clarify and differentiate these terms. This section focuses specifically on augmented guitars, acoustic or electric guitars that have been extended with additional sensing or computational capabilities. One of the earliest definitions of augmented instruments characterizes them as traditional instruments extended with one or more sensors [6]. In practice, the augmentation of guitars has taken on many forms, each driven by different motivations.

2.1.1 Examples of Augmented Guitars

Projects like the *Multimodal Guitar Toolbox* [7] combine audio-derived features (e.g., polyphonic pitch estimation) with sensor data (e.g., force-sensing resistors) to modulate digital audio effects via custom-designed mappings. The *RANGE* system follows a similar vision, viewing the guitar as a flexible platform for control. It integrates multiple input modalities, such as sensors and potentiometers, with onboard digital signal processing (DSP) and embedded computing. It also supports user-facing programming environments like *Max*[1], allowing musicians to implement custom augmentations

[1] Max is a visual programming language tailored to audio processing applications: `https://cycling74.com/products/max-9`

themselves [8].
Some projects explore more specific aspects of guitar interaction. Hödl and Fitzpatrick, for instance, examine the range of hand gestures that can be detected during performance, and how these gestures might be used as expressive control parameters [9]. The *GuitarAMI* system embeds various sensors (including accelerometers and ultrasonic rangefinders) into the guitar body to enable real-time timbral manipulation, processed through environments like *Pure Data*. By contrast, *GuiaRT* focuses on higher-level symbolic interaction. It analyzes hexaphonic audio input to extract low- and mid-level descriptors, and then triggers responses from a sample-based audio library to simulate ensemble-like interaction [10].
In other cases, augmentation serves to support peripheral tasks associated with guitar practice and performance. One such example is a guitar system designed to facilitate learning and rehearsal by streamlining common interactions with digital media. This includes capabilities like precise transport to particular musical sections or automatic scrolling of digital lyrics, which are tasks traditionally handled via external devices such as mice or keyboards [11].

2.2 Actuated Instruments

Actuated instruments can be understood as a subset of augmented instruments, distinguished by their ability to modify the physical behavior of the instrument itself via embedded transducers. In these instruments, tangible vibrating elements, such as strings or resonant surfaces, become the primary focus of interaction between the performer and the instrument [12]. Actuation is typically accompanied by a feedback path through the instrument, enabling a dynamic interaction in which performer actions and acoustic responses are deeply entangled.

2.2.1 Examples of Actuated Guitars

Lähdeoja's augmented guitar processes a hexaphonic input, providing one signal per string, through the *Max* environment to drive two sound drivers attached to the body of an acoustic guitar [13]. The resulting output propagates directly through the guitar's body, without external amplification, creating immersive and nuanced acoustic effects. The presence of a feedback loop can also lead to indefinite string sustain, although this was not the primary focus of the project.
On the commercial side, products like the *HyVibe Smart Guitar*[2] and Yamaha's *TransAcoustic Series*[3] integrate digital effects and looper units directly into the guitar body. These systems transform the guitar itself into a loudspeaker, amplifying the string signal

[2]Website from HyVibe: `https://www.hyvibeguitar.com/`
[3]Yamaha's TransAcoustic product page: `https://de.yamaha.com/de/products/musical_instruments/guitars_basses/ac_guitars/ta_2024/index.html`

along with embedded effects. Importantly, they are designed to avoid self-oscillating behavior. The signal path remains feedforward-only, either excluding the processed signal from the feedback loop or actively canceling it. A similar approach is taken by the *ToneWoodAmp*[4], which provides attachable acoustic actuation through the guitar's back plate.

2.2.2 Towards a Typology of Actuation

Within the broader category of actuated instruments, distinctions begin to blur. Some instruments emphasize complex, self-oscillating behavior characteristic of feedback-actuated systems. Others aim for precise control over the instrument's physical response by manipulating parameters such as damping, stiffness, or mass [14]. These variations suggest a spectrum of design approaches, with different systems positioned according to how much control is exerted over vibrational energy, and how much autonomy is allowed for evolving acoustic feedback.

2.2.3 Self-resonating guitars

The *Feedback Resonance Guitar* by Berdahl arguably fits both the category of self-resonating instruments and smart instruments. Through electromagnetic actuation, the strings of an electric guitar can be driven by either its own pickup signal, a pre-recorded or computer-generated sound, or through the instruments of co-performers. The various input modes enable a self-sustaining behaviour, with possible audio processing steps performed in the feedback path. It can also be considered a smart instruments in terms of co-performing with other musicians over the internet, which they demonstrated in a network performance [12].
The feedback lap steel also fits this segment. It closes a feedback loop around the body and strings of a lap steel guitar. The string vibrations are picked up with a traditional electromagnetic pickup and fed back using a tactile transducer mounted underneath the bridge. The strings can oscillate without continuous excitation, and the feedback loop is kept stable by varying effect parameters of effects like filters, or delays in the feedback path[15].
Finally, the *Halldorophone* is one example worth mentioning, even though it is not a guitar. Instead, it's a modified or a resemblance of a cello that is involved in multiple string-dependent feedback loops. Using various physical control elements akin to a mixer, the feedback can be controlled per string or set of strings [16]. The instrument has evolved over ten years, and is featured in various well-known compositions, rendering the project a seminal work in the field of self-resonating instruments.

[4]ToneWoodAmp website: `https://www.tonewoodamp.com/`

2.2.4 Actively controlled guitars

Actively controlled instruments can be seen as a separate segment insofar as they are motivated by a specific control objective. Historically active control has been more concerned with the suppression of vibration rather than its initiation [17, 14, 5]. A simplified nuance could thus be found in the ability of the instrument to be actively damped, which poses stronger challenges as the control (feedback) signal needs to be reinjected into the structure with the right phase for destructive interference to occur and it requires more control output power[18]. This poses tighter requirements on the system implementation, which makes it fair to say that an active control system could likely also be used as a self-resonating instrument, while the opposite is not necessarily true.
In that stricter notion, the concept was elaborated upon in various applications. Where Griffin was interested in acoustic replication, i.e., transposing the acoustic qualities of the body from a specific instrument to another [3], Besnainou saw active control as a new way of sound synthesis [14]. In their view, this could create a new instrument-musician relationship in which intimacy with the original instrument is preserved, yet expressive capabilities are expanded upon. Berdahl and Smith also described this approach as physical audio effects [19]. They showcase various audio effects that are physically applied to a guitar string. By actively damping it and modulating the amount of damping effects such as amplitude modulation (AM), it can be achieved. Various effects can be plugged within the loop by using a dynamic range limiter within the feedback path that adjusts the gain according to a desired root-mean squared (RMS) level value. The authors achieve diverse physical effects such as sustain, ring modulation, or even frequency modulation with these techniques.
On the commercial side, the Moog Guitar, introduced in 2008 by Moog Music, represented a significant commercial attempt to integrate active control into a traditional electric guitar form factor.[5] This instrument allowed performers to manipulate the sustain characteristics of each string independently, including real-time transitions between infinite sustain, natural decay, and rapid damping. Demonstrations by artists such as Lou Reed highlighted the expressive potential of the system. Despite its technical novelty, the Moog Guitar failed to achieve widespread adoption. Its high retail price (over $5,000) likely posed a substantial barrier to entry. While exact implementation details are not publicly documented, it is reasonable to assume that each string was individually sensed and actuated using per-string electromagnetic systems, enabling nuanced control over vibration energy. The *VO-96* iterated on the Moog Guitar, allowing mode-dependent damping and sustain, through which the strings produce interesting sounds[6]. It too seems to be discontinued. The prototype of the *phase8*[7] gives an outlook on how active control could be embodied in a synthesizer. Using familiar synthesizer controls, the

[5] See Moog Guitar archive: `https://web.archive.org/web/20100823001427/http://www.moogmusic.com/moogguitar/`

[6] News article regarding the *VO-96*: `https://experimentalsynth.com/vo-96/`

[7] Product page of *phase8*: `https://korg.berlin/products/phase8`

excitation, temporal dynamics, and timbre of kalimba-like tines are controlled and sequenced. The tines can also be physically interacted with, promising an interesting blend of digital and acoustic elements.
Various sustainer systems are commercially available, such as those engineered by Sustainiac[8], Fernandez, or provided as an open-hardware do-it-yourself (DIY) option[9]. These systems are similar to the Moog Guitar by providing infinite sustain and a harmonic mode that changes the timbre of the strings. Yet they are less elaborate than the Moog Guitar in that control options for performers are limited to just these two modes. Due to these limitations, they neither perfectly fit the segment of active control, nor due they fit the self-resonating category well, as they lack the evolving and complex behavior observed in the other examples given.

2.3 Smart Instruments

The label "smart" is used inconsistently across the literature when referring to musical instruments. In this thesis, smart guitars are considered a distinct category, related to actuated instruments but with different motivations. The term aligns with the broader usage of "smart" in consumer technology, typically referring to devices that are connected to the Internet of Things (IoT) and include embedded computation and communication capabilities.
Turchet defines smart musical instruments as “devices dedicated to playing music, which are equipped with embedded intelligence and are able to communicate with external devices” [20, 21]. This definition frames smart instruments less in terms of physical interaction and more in terms of networking, data exchange, and extended functionality through connectivity.
A prominent example is the *Sensus Smart Guitar*, which integrates embedded sensors, onboard processing, and wireless communication. It supports the transmission and reception of MIDI, Open Sound Control (OSC), and audio data. Use cases include real-time remote collaboration and integration with smart sensor networks [22]. An earlier implementation of the smart paradigm included a guitar with remote sound processing controlled via a Wii-based gestural interface [23].
Although smart guitars employ advanced sensing and computation, they are generally not concerned with shaping the instrument’s acoustic response through physical feedback or control. For this reason, they are only tangentially related to the topic of active control and will not be a central focus of this thesis.

[8] Sustainiac’s sustainer: `https://www.sustainiac.com/st-pro.htm`
[9] Open-hardware DIY sustainer: `https://bitbucket.org/metalmarshmallow/mm-diy-sustainer/src/main/`

2.4 Theoretical Foundations of Active Control

Active control has its roots in fields such as civil and mechanical engineering, where it is commonly employed to suppress unwanted vibrations in large structures subject to external forces like earthquakes or wind [24]. When applied to acoustic musical instruments, the same principles allow for precise manipulation of the instrument's vibrational behavior, thereby altering its sound radiation characteristics. This capability opens up new possibilities for musical expression while preserving the familiar physical interface of traditional instruments [14].
There are several motivations for exploring active control in the context of musical instruments:

1. **A "programmable" acoustic instrument**: Musicians often own multiple instruments of the same class, each valued for its unique timbral qualities. However, collecting and transporting these instruments can be impractical or costly, especially in the case of prestigious examples like a Stradivari violin. An actively controlled instrument could be made to emulate various timbral signatures on demand, allowing musicians to prioritize ergonomic or aesthetic aspects without sacrificing sonic variety [18, 25].

2. **Timbre manipulation beyond the usual**: With active control, it becomes possible to alter an instrument's dynamic behavior in ways not achievable through passive means. This includes effects such as infinite sustain, artificial damping [26], or spectral reshaping by influencing specific vibrational modes.

3. **Feedback suppression in amplified settings**: When acoustic guitars are amplified via loudspeakers, unwanted feedback loops can arise. The sound from the speaker may re-excite the guitar body or strings, producing howling tones that distract from performance. Typically, performers compensate by altering their positioning relative to the speaker, which increases cognitive load. Active damping techniques can automatically suppress such feedback without degrading the instrument's tonal character [5].

2.4.1 Modal Control

Modal control aims to manipulate an object's vibrational response by targeting its individual resonant modes [4]. These modes, defined by their frequencies, amplitudes, and decay times, are key determinants of an instrument's perceptual attributes, such as pitch, timbre, and temporal character [27].

Proportional-Integral-Derivative (PID) Control

One approach to modal control models each mode as a damped harmonic oscillator [25]. The restoring force u is defined as:

$$m\ddot{x} + R\dot{x} + kx = F = -u, \tag{2.1}$$

where m, R, and k are the mass, damping, and stiffness coefficients, and x, $\dot{x}$, and $\ddot{x}$ denote displacement, velocity, and acceleration, respectively. This formulation enables the use of PID control by modifying the coefficients of the system:

$$(m + P_{DD})\ddot{x} + (R + P_D)\dot{x} + (k + P_P)x = 0, \tag{2.2}$$

Here, P_{DD} corresponds to an acceleration-proportional term, P_D to a velocity-proportional term, and P_P to a displacement-proportional term. Berdahl envisioned this method as a stateless controller capable of simultaneously affecting multiple modes with minimal configuration. Musically, it allows for damping, sustaining, and even minor frequency shifts affecting several resonances at once, though without any mode-specific parameters. When the modal shapes of a structure are known or have been pre-identified, multiple PID controllers can be applied to target individual nodes with high precision. This has been demonstrated in simplified setups involving strings [4, 28, 29, 3], as well as practical implementations for objects such as xylophone bars [30] and experimental wind instruments [31].

Filter-Based Control

One limitation of PID control is its reliance on accurate, prior system identification, a difficult requirement when working across different instruments, even among those built by the same luthier. To address this, filter-based control strategies use parallel bandpass filters in the feedback path, each tuned to a mode of interest [32]. Unlike PID control, this approach does not require an analytical model of the system. It operates entirely in the frequency domain.

Importance of Sensor-Actuator Collocation

Berdahl extensively explored modal control systems and their stability properties [18]. A key insight is that many controllers used for damping, whether PID, bandpass, or notch-filter based, are passive: they only remove energy from the system. This passivity guarantees unconditional stability, which is typically desirable in musical contexts. However, to ensure true passivity, the sensor and actuator must ideally be collocated, that is, they should operate at the same physical point on the instrument. While perfect collocation is impossible in practice, small spatial discrepancies are usually tolerable. Larger distances, however, introduce phase delays due to wave propagation, which in turn affect system stability and reduce the effective control bandwidth.

These delays can theoretically be compensated for, but doing so becomes complex in the presence of frequency-dependent effects such as dispersion. Moreover, when the injected and measured energy propagate along different paths, accurately modeling their interaction becomes significantly more difficult.

2.4.2 Traveling Wave Control

While modal control dominates the literature and forms the basis of this thesis, traveling wave control presents an alternative strategy that may offer theoretical advantages. Modal control interprets vibrations as standing waves, the result of interfering traveling waves. In contrast, traveling wave control operates directly on the traveling waves themselves. This method involves detecting a traveling wave along the medium, such as a vibrating guitar string, and actuating a termination point (e.g., a bridge or damper) to cancel it at the appropriate moment with the correct amplitude. If performed perfectly, no standing wave would form at all.

To the author's knowledge, Donovan's thesis provides the most detailed application of this technique in the context of stringed instruments [27]. While the theoretical potential is acknowledged, Donovan also highlights significant practical challenges.

The method is highly sensitive to wave speed, which is a function of string tension and length. Accurate control would require real-time pitch tracking to estimate propagation delays precisely. Although small differences due to fingering positions may be negligible, they still reduce the effectiveness of the control.

Furthermore, the system must compensate for nonlinearities inherent in sensors and actuators. Donovan's implementation required custom-built optical displacement sensors for wave detection and piezo-stack actuators to avoid electromagnetic nonlinearities. Although successful damping was demonstrated, the complexity of the setup currently limits the feasibility of this approach for broader adoption in musical instrument research.

2.5 Designing for Musical Expression

Musical expression is a multifaceted and somewhat elusive concept. Fels argues that expressiveness arises from the relationship that forms between a musician and their instrument [33]. Following Moore's concept of "control intimacy," he emphasizes that instrument design should support the development of such relationships [34]. In an intimate performer-instrument relationship, the control exerted by the musician closely maps to the resulting sound, enabling the artist to express intention and emotion through the instrument.

The formation of musical control intimacy is inherently embodied. Nijs et al. [35] identify two key aspects: first, instruments must offer perceptible affordances, opportunities for interaction and expression that can be executed body-schematically, without deliberate cognitive reflection. This supports quick and intuitive responses to cues from the musical

context, such as co-performers or audience interaction. Second, this intuitive engagement is complemented by goal-oriented practice, through which musicians shape internal models of the instrument and their performance. Over time, these models guide the refinement of skill and enable deep expressive control.
Digital musical instruments (DMIs) are often criticized for lacking this sense of intimacy [36]. One contributing factor is the absence of primary haptic feedback, physical responses that emerge directly from interaction with the instrument. In acoustic instruments, energy flows naturally from performer to object and back again, forming a tightly coupled feedback loop. DMIs, by contrast, decouple control from sound generation, which allows for arbitrary mappings but often weakens the embodied relationship [37, 38].

2.5.1 Augmented Instruments as Expressive Platforms

Augmented instruments attempt to address this disconnect by building upon existing instruments that have historically facilitated expressive performer-instrument relationships. The electric guitar, for instance, is itself an augmented instrument. Originally developed to amplify sound, it quickly evolved into a highly expressive tool in its own right [2]. Experienced guitarists frequently personalize their instruments, changing string types to affect sustain and feel, modifying effect pedals to shape tone, or installing custom pickups such as sustainers. This continuous tinkering places the guitar in a "constant state of change" [39]
Given the strong sense of sonic ownership that guitarists often exhibit, the question arises: how can the guitar be meaningfully augmented further? Professional guitarists have recognized the value of the integrated vision of smart guitars, yet authors note that this approach often shifts the skill burden from musical to technological expertise [40]. Programming mappings, configuring sensing systems, and debugging the platform can disrupt creative flow. Furthermore, the lack of immediate physical feedback undermines the embodied responsiveness needed for expressive play.
The design approach taken in this thesis aligns more closely with the concept of actuated instruments and especially those involving elements of active control. These instruments enable tangible interactions through controlled feedback, allowing performers to exploit effects based on sustain, resonance, or damping. Active control, as outlined in section 2.4, offers a promising theoretical foundation for this kind of shapeability. By rediscovering familiar audio effects (e.g., reverb, delay) in the feedback path rather than the feedforward path, guitarists gain new expressive possibilities while maintaining a physical and intuitive connection to the instrument.
Because augmentations inevitably build upon preexisting practices, it becomes essential to evaluate their effect on the preexisting musician-instrument relationship. Section 2.6 introduces a methodological approach drawn from HCI that is particularly suited to this contextual and experiential form of evaluation.

2.6 Evaluating with Design Probes

The concept of *cultural probes*, introduced by Gaver et al. [41], has found widespread application in human-computer interaction (HCI) research. While probes resemble prototypes in that they are functional artifacts, they serve a different purpose. Rather than being used to extract requirements or validate solutions, probes are designed to provoke, disrupt, and inspire. They are situated in real-world contexts to elicit rich and often ambiguous responses from participants [42].

Boehner et al. [43] distinguish between two major uses of probes: some researchers view them as data-gathering tools, while others value them for their ability to foster reflection and dialogue. The latter perspective seems especially well-suited to the domain of musical instrument design, where subjective experience, emotional response, and cultural meaning are central.

Rather than attempting to reinvent the instrument entirely, this thesis aims to extend what already exists. From this perspective, the instrument is not merely a physical object but part of a broader assemblage; its material structure, social use, historical development, and performance practice all contribute to its identity. Waters [39] captures this view, which aligns with Tahıroğlu et al.'s concept of a musical instrument as a "mode-of-being" [44]: an evolving relationship between performer and instrument embedded in context, culture, and intention.

Digital musical instruments, when implemented as design probes, can serve as cultural artifacts that challenge assumptions about musical interaction. They invite new perspectives not only during performance but also through the act of design itself. Probes can reveal subtle dynamics in performer-instrument relationships, spark new modes of engagement, or cause reflection in the constitution of performance [45].

In this work, probes are used to explore the relationship between guitarists and their instruments. Guitarists often engage in a long-term, iterative process of personalization, through choice of strings, pickups, pedals, and sustainers, leading to a deeply embodied understanding of their instrument. Over time, the instrument becomes increasingly "transparent" [35], allowing for expressive intent to be conveyed with minimal cognitive mediation.

Augmented instruments, deployed as probes, offer a direct and embodied means of provoking response. Rather than relying on abstract speculation interactions, the probe exists within the performer's lived context. In doing so, it can reveal not just how new features are used, but how they transform the relationship to the instrument itself.

Because this evaluation approach embraces exploration and context, it inherently resists narrow or quantitative conclusions [43]. Instead, ambiguity is treated as a design resource that broadens the conceptual and experiential space in which augmented acoustic guitars are designed.

Chapter 3

Control system implementation

As established in section 2.4.1, collocated sensing and actuation simplify the implementation of active modal control, enhancing both stability and effectiveness. Inspired by Davison et al's prior work on self-singing haptic actuators[1], the usage of current-sensing amplifiers seemed an avenue worth exploring for the application in active control. A kit including a custom printed circuit board (PCB), the voice-coil actuator, and a Teensy 4.0 microcontroller was kindly provided by the authors. It was used to pilot the control system implementation and gather early insights on the feasibility of the control strategy. Due to reliability issues and the anticipation that additional audio inputs and outputs might be needed in the final design probe implementation, an adapted PCB based on the original has been designed and manufactured. The details of which are outlined in this chapter, alongside the software implementation of the control system.

3.1 System setup

The system's hardware comprises three broader elements:

A voice coil actuator (VCA) able to both induce and estimate vibrations via current

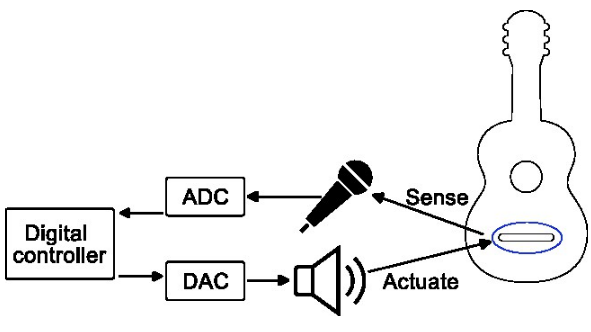


Figure 3.1: High-level system diagram

sensing, enabling collocated actuation and measurement. A Dayton Audio EX32VBDS-4 Voice Coil Transducer[1] was used which is intended to be mounted on rigid surfaces and offers 40 W power output.

A current-sense amplifier that serves as both digital-analog converter (DAC) for the control signal output from the digital controller and analog-digital converter (ADC) for the current-sensing output. Operating the current-sensing at audio frequencies enables the simultaneous operation of amplification and measuring.

A digital processing unit processing the input signal with minimal processing latency to produce a control signal driving the VCA to achieve a control goal.

3.1.1 Electronics design

Building on their prior work[1], Davison et al. developed a kit[2] to operate sound transducers as collocated devices. The kit is designed for use with the Teensy 4.0 microcontroller[3] and features the Max98389[46], a Class-D amplifier with a current-sensing output channel. This kit supported initial feasibility and technical exploration, with provided firmware exposing a USB interface recognized as an audio device by the host computer. Its ease of use and comprehensive documentation further streamlined tasks such as modal characterization.
However, due to the strict latency requirements of the control system, an alternative processing platform was adopted. The Daisy Seed[4] was selected for its ability to operate with an audio block size of four samples, corresponding to a processing delay of just 0.08 ms at a 48 kHz sampling rate. It also offers the necessary interfaces for communicating with the amplifier: inter-integrated sound (I^2S) via its serial audio interface (SAI) peripheral and inter-integrated circuit (I^2C) for configuration tasks. Additionally, an onboard codec provides two additional input and output channels, which become relevant for the final instrument design.
The original schematic, designed for the Teensy 4.0 platform, was modified to accommodate the Daisy Seed. As both platforms operate at the same voltage, only minimal adjustments were required. The logic signals of the Max98389 operate at 1.8 V whereas the Daisy Seed provides 3.3 V signals. The I^2C signals are converted by a simple bi-directional MOSFET level shifter. The I^2S clock runs at 1.536 MHz, compared to just 400 kHz for I^2C. Therefore, a dedicated I^2S level shifter converts the level, avoiding potential timing issues. The revised schematic is available in the appendix A and a photograph of the PCB can be seen in figure 3.2. Acknowledgment is due to the original

[1]Dayton Audio EX32VBDS-4 Voice Coil Transducer datasheet: `https://www.daytonaudio.com/images/resources/295-275--dayton-audio-ex32vbds-4-spec-sheet.pdf`

[2]Self-sensing amplifier kit: `https://github.com/davisonaudio/HapticInstrumentWorkshop`

[3]Teensy 4.0 development board: `https://www.pjrc.com/store/teensy40.html`

[4]Electro Smith's Daisy Seed: `https://daisy.audio/hardware/Seed/`

creators of the amplifier kit, whose work served as a foundational reference and who kindly provided a kit.

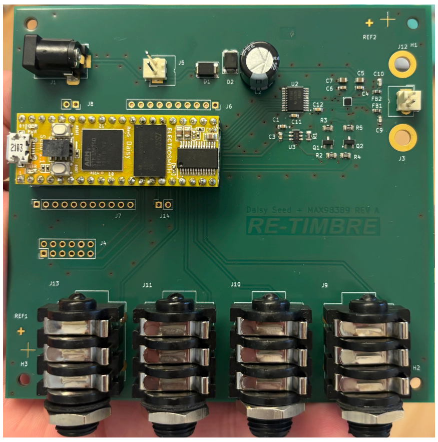


Figure 3.2: Photograph of the manufactured and assembled PCB. In the top left corner, there are the 9 V power supply for the Max98389, and the microcontroller. The bottom section includes two 6.3 mm sockets connected to the Seed's onboard audio inputs and two connected to its outputs. The top right section shows components related to the Max98389 and the connector for the actuator.

3.1.2 Actuator placement

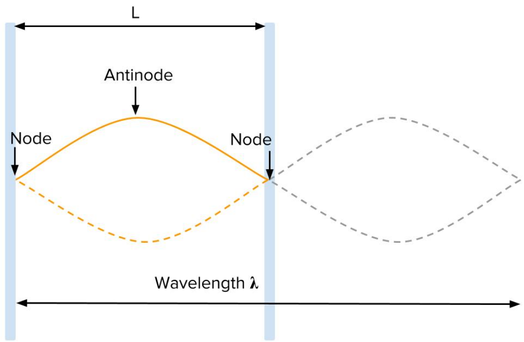


Figure 3.3: Model of a standing wave, showcasing the movement at nodes compared to anti-nodes. Image source (last accessed: 21.05.2025): `https://www.khanacademy.org/science/in-in-class11th-physics/in-in-11th-physics-waves/in-in-class11-standing-waves/a/standing-waves-review-ap`

Care must be given to the placement of the collocated actuator. The body of an acoustic guitar inhibits structural nodes, anti-nodes, and the space between (see figure 3.3). Nodes are points of no vibration. Thus, neither observing nor exciting the corresponding mode is possible. The opposite is the case for anti-nodes. Here, the displacements caused by the vibration are the largest, making it an ideal control location [47]. In practice, the actuator is unlikely to be placed exactly on a node or anti-node. Furthermore, the actuator does not truly sense or actuate at a single point, but over a finite surface area. Yet, there will be locations from which desired modal frequencies can be controlled more effectively than others, warranting a modal characterization of the system.

Modal analysis

As established in section 2.4.1, a full-fledged characterization may not be needed to find actuator locations with sufficient modal control when using bandpass filter control. Therefore, a practical measurement approach was adopted in which frequency response measurements were taken on 13 distinct points on the guitar body (see figure 3.4).
The voice coil actuator has been used as a measurement device by placing it on each point. The guitar was excited by tapping the guitar bridge with an improvised impact hammer. The guitar bridge couples the strings to the guitar body, so that the sound of the strings can be injected. It was therefore chosen as a suitable excitation point. For each measuring location, three impulse responses were recorded. Each recording was normalized, and the calculated magnitude responses were averaged for each location. The result was one final magnitude response plot for each location.

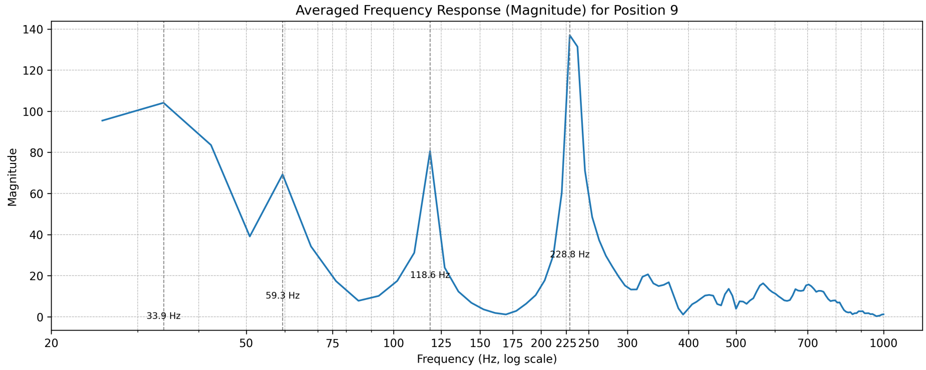
Figure 3.4: Measurement points on the guitar body.

Mode	F0 (Hz)
1st	59.3
2nd	118.6
3rd	228.8

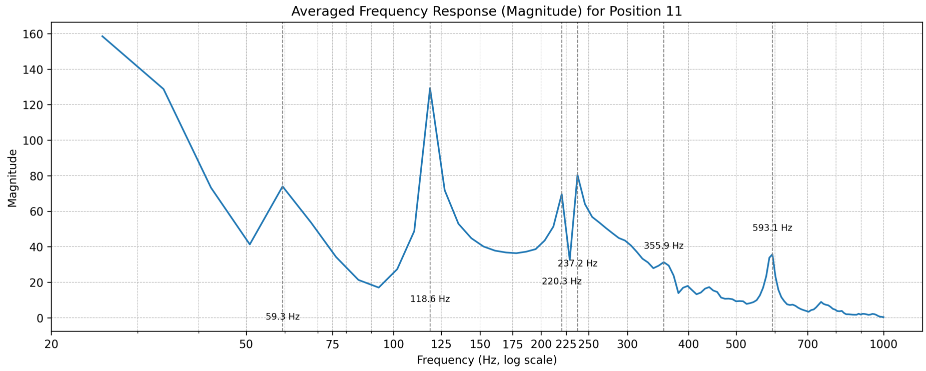
Table 3.1: Frequencies for Different Modes

Results

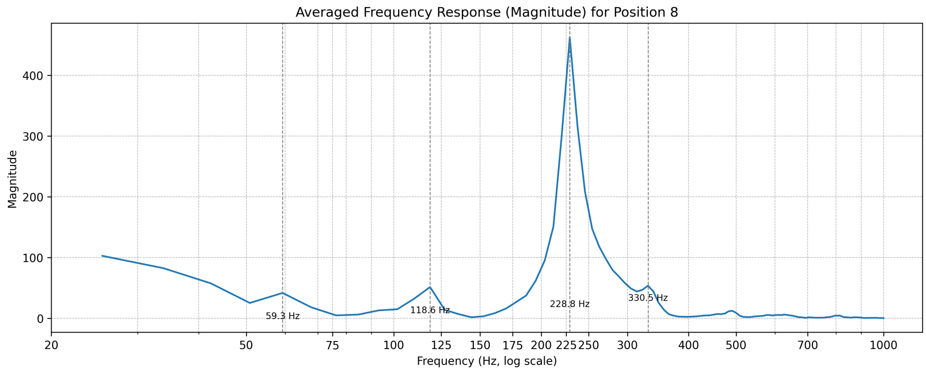
Figure 3.5a depicts the magnitude response measured at location 9. Here, three resonant peaks are visible, suggesting the presence of individual modal frequencies (see table 3.1). The frequency responses recorded at the other locations follow a similar pattern with some shifting in frequency occurring, especially in the presence of a notch. The notch around 228 Hz in the frequency response of position eleven indicates that this location might be close to a nodal line for the 3rd mode (see fig 3.5b). In contrast, location 8 might be close to an anti-node as indicated by the very high magnitude value for the third mode. These results informed the actuator placement used in the control experiments described in Chapter 4.



(a) Frequency response measured on location 9



(b) Frequency response measured on location 11



(c) Frequency response measured on location 8

Figure 3.5: Frequency responses measured through the current sense channel of the voice coil actuator at selected locations

3.2 Software Design

The software running on the Daisy Seed performs the DSP operations necessary to calculate the control signal based on the input signal to achieve the control objective. Berdahl's bandpass filter design will be used to damp targeted modes[25]. Auxiliary tasks such as configuring Seed's peripherals to be able to communicate with the external hardware, as well as configuring the external hardware itself, are left out for brevity.

3.2.1 Bandpass filter control

The bandpass filter proposed by Berdahl et al. [25]:

$$K_{bp}(s) = K_0 \frac{\frac{2\pi f_c s}{Q}}{s^2 + \frac{2\pi f_c s}{Q} + (2\pi f_c)^2} \tag{3.1}$$

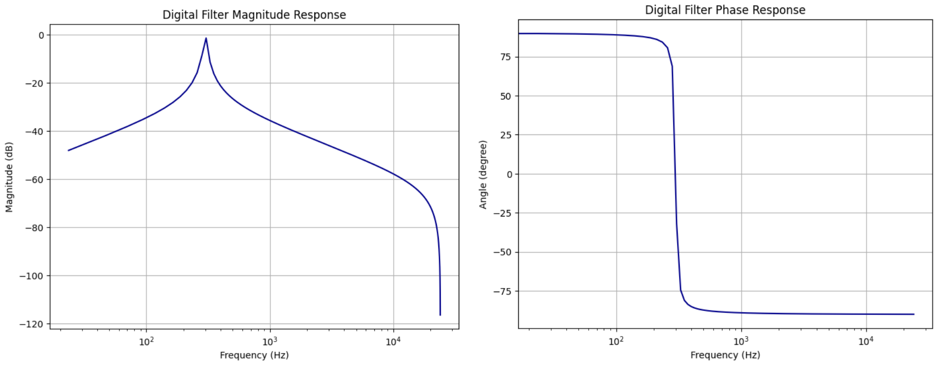
can be used to apply damping selectively to a narrow frequency range around the center frequency f_c, with a bandwidth determined by the quality factor Q.
The transfer function in Eq. 3.1 describes a standard analog second-order bandpass filter, where the numerator is first-order in s, reflecting a single differentiating term. The coefficients for the analog filter are derived by expressing the transfer function as a ratio of polynomials:

$$K_{bp}(s) = \frac{b_0 s + b_1}{s^2 + a_1 s + a_2} \tag{3.2}$$

Substituting from the standard form yields:

$$b_0 = K_0 \cdot \frac{2\pi f_c}{Q}, b_1 = 0, a_1 = \frac{2\pi f_c}{Q}, a_2 = (2\pi f_c)^2 \tag{3.3}$$

These analog coefficients are then used with the bilinear transform to design a second-order infinite impulse response (IIR) digital filter. Figure 3.6 shows the frequency response of the digital filter configured with $f_c = 300\,\text{Hz}$ and $Q = 20$.
The magnitude response shows strong attenuation of frequencies away from f_c, enabling targeted control. The phase response reveals that the phase offset is near zero at f_c, meaning that the control signal is in phase with the measured velocity. This phase alignment is what produces damping, since a control force in phase with velocity extracts energy from the system [25].



(a) Magnitude response **(b)** Phase response

Figure 3.6: Response of digital filter.

Chapter 4

Experimental Validation

This chapter presents the experimental validation of the active control system developed to modify the vibrational behavior of an acoustic guitar. The effectiveness of the system is evaluated by comparing top-plate impulse responses in open-loop (control off) and closed-loop (control on) configurations, under the constraints defined in Chapter 3. In addition, the system's capability to sense vibrations induced by the guitar strings is assessed. This is achieved by estimating the signal-to-noise ratio (SNR) from the current-sense signal when a string is plucked versus unplucked. To address initially low SNR values, a soundpost was introduced to effectively pre-load the voice coil actuator, and the resulting SNR improvement is compared to the unloaded case.

4.1 Structural control

Structural control as one validation step has been chosen due to its relative simplicity compared to string modal control. The voice coil actuator under test can be directly attached to the guitar's top plate, and the mechanical coupling to the strings can be neglected. This serves as an initial exploration and feasibility estimation of the designed control setup.

4.1.1 Objective

The experiment's objective is to validate whether the designed control system can effectively attenuate selected resonances of the guitar body, particularly the first air and plate modes. The damping of modes is particularly relevant for the validation, as it is typically harder to achieve than sustaining [19]. This is because the controller needs to compensate for the energy present externally added to the system under control, which requires more power than merely adding energy. Furthermore, the excitation caused by a hit with the impulse hammer is instantaneous, and resonances are short-lived, while the control system will inevitably have some delay. Showing the system's ability to dampen these structural vibrations will thus give solid insights into the design's feasibility for later musical exploration.

4.1.2 Experiment Setup

To isolate body-level effects, all strings were removed. A PreSonus PRM1 Precision Reference Microphone[1] was used to record the guitar's impulse responses. Recording with an external microphone, rather than monitoring the actuator's current output directly, ensures that any observed changes reflect global vibrational modifications of the guitar top, rather than localized phenomena due to sensor-actuator collocation. All recordings were conducted in an anechoic chamber to minimize interference from reflected acoustic energy.

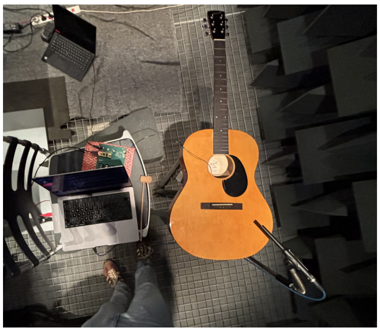


Figure 4.1: Photo taken during the experimental validation

All recordings were conducted with the actuator physically attached to the guitar. For the open-loop (control off) condition, the actuator was left unpowered; for the closed-loop (control on) condition, the controller was active. The structure was excited at the bridge using a makeshift impulse hammer. While suboptimal for exciting higher frequencies, the hammer sufficiently energized the frequency range of interest for this study. As the evaluation does not aim to compare different modal frequencies with each other, the uneven frequency response of the hammer was considered acceptable.
Due to the uncontrolled impact, causing variations in velocity, timing, and position, each test was repeated three times. To mitigate the effects of these inconsistencies, the signals were normalized and averaged across trials. Power spectral densities (PSDs) were computed using the Welch method [48] and averaged to reduce the influence of random fluctuations.
To estimate the modal decay times, each signal was bandpass filtered using a 4th-order Butterworth filter centered at the modal frequency, with a 10 Hz offset between the -3 dB cutoff points and the center frequency. Signals were temporally aligned using cross-correlation, and the analytic signal was extracted via a Hilbert transform. The

[1] https://de.presonus.com/products/prm1-precision-reference-microphone

amplitude envelope was then estimated as the magnitude of the analytic signal. Decay time was defined as the duration required for the envelope to drop to a one tenth of its maximum value.

4.1.3 Results

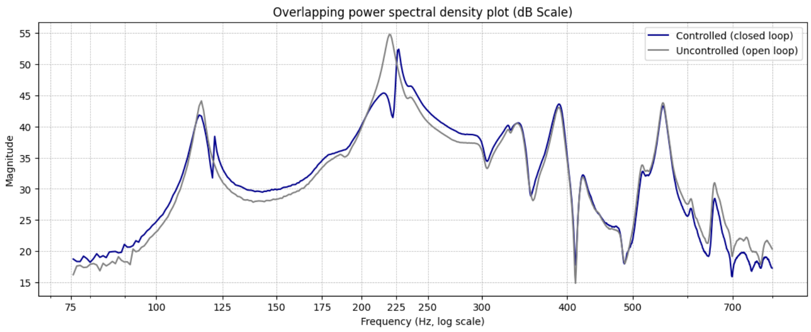
The results of the closed-loop and open-loop measurements are shown in Figure 4.2.

Observation

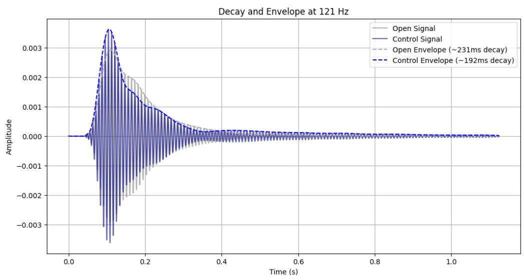
The closed-loop response exhibits a clear reduction in magnitude at both the first air mode (120 Hz) and the first plate mode (224 Hz). Notches appear at the targeted modal frequencies, while other frequency components remain largely unaffected. These notches exhibit high-Q behavior (narrow bandwidth) and are often preceded or followed by a local amplitude peak. Compared to the open-loop case, the notch near 120 Hz in the closed-loop response is not perfectly aligned with the corresponding open-loop modal peak. As a result, a residual peak remains at this frequency, albeit with a slightly reduced amplitude. For the plate mode, the notch at approximately 224 Hz is followed by a secondary peak near 226 Hz, which appears slightly shifted relative to the open-loop response.
The estimated decay times of the modal envelopes are reduced by approximately 39 ms at 121 Hz and 23 ms at 224 Hz. Both envelopes exhibit a faster decay rate under closed-loop control compared to the open-loop case. Notably, the envelope at 121 Hz shows a non-monotonic behavior, with a brief increase in amplitude prior to the final decay phase.

Interpretation

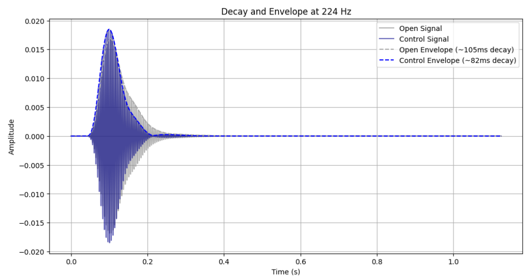
These observations indicate that the active control system is capable of attenuating the first air and plate modes of the guitar body. However, the reduction in decay time is modest—on the order of a few tens of milliseconds. This raises the question of whether such a change is perceptible to human listeners. According to psychoacoustic studies on the just-noticeable difference (JND) in decay time, listeners can detect differences of approximately 20 ms to 30 ms for frequencies above 100 Hz [49]. Given these thresholds, it is plausible that the achieved damping could be perceptible in controlled listening environments.
Nevertheless, it is important to note that, for the sake of reproducibility and isolation, the resonances in this experiment were excited via impulse hammer impacts. In actual musical scenarios, structural resonances are typically excited more subtly through string vibrations rather than discrete impacts. Therefore, the relevance of these results to musical contexts involving continuous string excitation remains uncertain.



(a) Power spectral density of the open-loop and closed-loop responses. Less power at ~ 120 and ~ 223 Hz can be observed



(b) Amplitude envelope and approximated decay time at 121 Hz



(c) Amplitude envelope and approximated decay time at 224 Hz

Figure 4.2: Comparison of the power spectral density and decay times of selected modes between the open-loop and closed-loop system.

4.2 String Signal Strength

In the context of acoustics and mechanical systems, impedance characterizes how much force is required to produce a certain velocity in a system [50]. However, when dealing with active control and electro-mechanical interaction, impedance must be considered as a property of the interaction between two systems, and in both directions. In this experiment, two distinct impedance relationships are relevant:

$$\begin{aligned} z_{\text{in}} &= \frac{F_{\text{actuator}}}{V_{\text{string}}} \\ z_{\text{out}} &= \frac{F_{\text{string}}}{V_{\text{actuator}}} \end{aligned} \tag{4.1}$$

Here, z_{in} represents the mechanical impedance seen by the actuator when driving the string, while z_{out} characterizes the impedance of the string as perceived by the actuator when used as a sensor. These expressions represent the bidirectional coupling between the actuator and the string: one in the actuation direction, the other in the sensing direction.

While collocation theoretically ensures stability and simplifies control design, it implicitly assumes that the actuator is equally effective in both transmitting and sensing energy. In practice, however, a voice coil actuator may exhibit asymmetric behavior: it may be effective in exerting force on the structure, yet insufficiently sensitive to motion when used for sensing. This asymmetry can undermine the advantages of collocation, especially if the sensing path yields a poor signal-to-noise ratio (SNR). This second experiment investigates the system's capability to sense string vibrations, as measured by the resulting signal-to-noise ratio (SNR). High SNR is crucial in feedback control systems, since any amplification of the feedback signal also amplifies noise - potentially leading to instability [18]. Informal testing suggested that the SNR would be relatively low. Therefore, this experiment not only measures the baseline SNR but also evaluates whether the addition of a soundpost can improve it. In violins, the soundpost is a structural element that asymmetrically couples the top plate to the back plate, affecting sound radiation characteristics [51, 50]. In the present context, the hypothesis is that the soundpost preloads the voice coil actuator such that forces exerted by the string induce larger coil velocities. This, in turn, would improve the actuator's sensitivity as a sensor and increase the effective SNR.

4.2.1 Experiment Setup

For this experiment, the strings had to be mounted on the guitar. However, only the low e string was excited and could vibrate freely. The remaining strings were muted by passively damping them with a thick piece of cloth. A consistent and repeatable excitation of the string is not possible without special equipment. To minimize variability,

a guitar pick excites the string in a sliding / slipping motion. Furthermore, for each series 20 plucks were recorded, so that an average SNR can be calculated.
The sensor used to record the audio stream is the current-sense channel from the audio codec. The signal-to-noise ratio (SNR) can be estimated by calculating the ratio of signal power to noise power. This is done by comparing a recording of noise only (no prior string excitation), denoted as x_n, with a recording of signal plus noise (capturing the string excitation), denoted as x_{n+s}. The root mean square (RMS) value of a signal x is defined as:

$$\mathrm{RMS}(x) = \sqrt{\frac{1}{N}\sum_{n=1}^{N} x_n^2} \tag{4.2}$$

To estimate the RMS of the isolated signal component, the power of the noise is subtracted from the total power of the signal-plus-noise recording:

$$\mathrm{RMS}_{\mathrm{signal}} = \sqrt{\mathrm{RMS}(x_{n+s})^2 - \mathrm{RMS}(x_n)^2} \tag{4.3}$$

The resulting signal RMS is then used to compute the SNR in decibels (dB):

$$\mathrm{SNRdB} = 20 \cdot \log 10\left(\frac{\mathrm{RMS}_{\mathrm{signal}}}{\mathrm{RMS}(x_n)}\right) \tag{4.4}$$

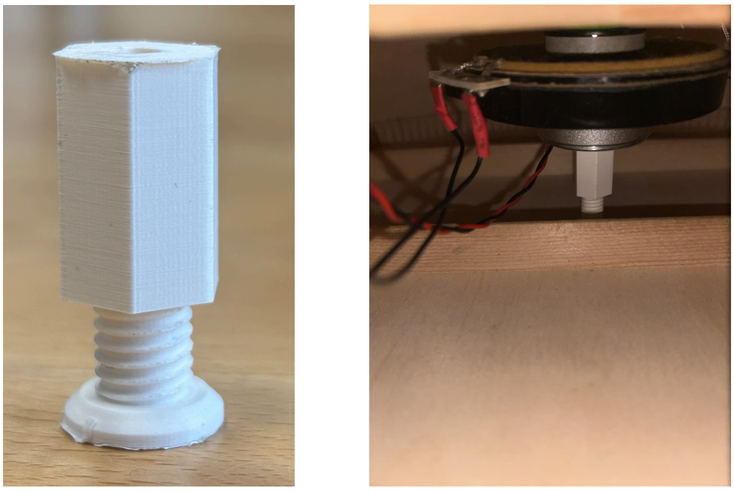
To validate the hypothesis regarding the soundpost, three series of the experiment have been conducted with different soundpost height configurations and using no soundpost at all. The soundpost has been designed to be height-adjustable by a screwing mechanism, so that the actuator pre-load can be configured (see 4.3).

4.2.2 Observation

The results can be inspected in the table 4.1. Overall, the SNR, regardless of the soundpost, is negative. The SNR values are the highest when the soundpost is extended by approximately 0.75cm, but decrease again with greater extension.

4.2.3 Interpretation

Visibly and audibly, the SNR is quite low regardless of soundpost configuration. A negative SNR value indicates that the sensed signal power is less than the noise power. Based on this observation, one can not conclusively state that the soundpost significantly improved SNR. The slight increase of 2,37 dB might be attributable to the presence of the soundpost; however, given the small extent to which SNR is increased, further investigation is not warranted. Furthermore, the increase is well within the standard deviation. Given the experimental variability (varying excitation strengths, relatively small sample size of 20 strikes per series), it can not be safely excluded this increase is



(a) 3D printed soundpost.

(b) Soundpost installed inside the guitar.

Figure 4.3: Images of the soundpost component.

due to parameter variations. While minor SNR improvements were observed with preload, these are likely within the bounds of experimental variability and do not substantiate a robust advantage from using a soundpost in this context.

Post extension	SNR (mean)	SNR (median)	SNR (std. dev)
no soundpost	-8.82 dB	-9.92 dB	4.31 dB
~0.75 cm	-6.72 dB	-7.55 dB	3.04 dB
~1.5 cm	-10.44 dB	-9.69 dB	2.83 dB

Table 4.1: SNR measurements for different soundpost extensions

Chapter 5

Design probes implementation

This chapter is concerned with the creation of a technology probe[43]. As introduced in section 2.6, design probes necessitate a combined view on design and evaluation. Design is not directed towards the creation and validation of a meaningful increment towards a clear value proposition, instead, its goal is to spark conversation. Therefore, this design chapter will not only feature the aspects of implementation, but also a description and hypothesis of what aspects each probe is expected to disrupt.

5.1 Design goals

The goals below are a baseline for both probe implementations. Both probes will further extend these based on their themes. To allow the musician to draw from their past playing experience, their repertoire of playing techniques should be preserved in a way that a technique yields an interesting outcome. The augmentation may enrich this outcome both sonically and haptically, or even assign new meaning to it. But existing gestures should not entirely disappear, allowing the probe tester to draw on their existing knowledge and skills.
The probe should provide a disruptive experience. Given that a guitarist might have prior experience with the usage of digital effects, particularly those in the feed-forward path, a forward-only audio effect seems insufficient. The probe should allow and promote emergent behavior in the musician–instrument interaction, which the musician might be more acquainted with when performing with other musicians.

5.2 Revisiting feedback control

So far, this thesis has been concerned with designing an active control system and evaluating it in a controlled lab setting. The original design showed promising results in the ability to control the top plate to some extent when struck percussively. However, it is

not sufficiently able to sense string vibrations. Therefore, an electromagnetic guitar pickup will be used to capture the string signal instead. It has the advantage of sensing the strings independently of the body, unlike piezo-based sensors. However, it operates nonlinearly, meaning the magnetic flux is not directly proportional to the string displacement. The inclusion of both horizontal and vertical information in the electrical signal of a pickup further complicates its usage in the active control system, especially with the goal of damping strings [52].
For these reasons and the lack of collocation, the implementation as a passive controller, which prevents issues of instability and can effectively damp vibrations, as Berdahl formalized, is not feasible [18]. The introduction of feedback can still be used to sustain a string, which can be considered as a form of active control, though the design possibilities are severely limited. A gain controller is introduced below, which controls how much the bridge is actuated with the feedback signal. This helps maintain an engaging state, though the feedback buildup can always be halted by muting the strings.

5.2.1 RMS Level Integral Gain Controller

Both probes share a common gain controller, similar to the design proposed by Berdahl and Smith [53]. This integral gain controller is configured to maintain the system in a dynamically engaging yet stable state. Rather than responding directly to instantaneous changes in loudness, the controller adjusts the feedback path gain gradually, in proportion to the accumulated error over time. Using integral control, rather than proportional or derivative methods, helps preserve the transients of the instrument and effect, and instead responds to the gradual build-up of loudness.
The controller modifies the post-effect feedback loop gain based on the root-mean-square (RMS) loudness $\mathbb{E}[n]$ of the discrete output signal $x[n]$, defined as:

$$\mathbb{E}[n] = \sqrt{\alpha \cdot \mathbb{E}[n-1] + (1-\alpha) \cdot x[n]^2} \tag{5.1}$$

The smoothing coefficient α is derived from a time constant τ (in seconds) and the sample rate f_s as:

$$\alpha = e^{-1/(\tau \cdot f_s)} \tag{5.2}$$

The error signal is defined as the difference between the current RMS level and the desired target RMS level $\mathbb{E}'$:

$$e[n] = \mathbb{E}' - \mathbb{E}[n] \tag{5.3}$$

The gain value $u[n]$ is then updated per sample using an integral controller:

$$u[n] = u[n-1] + K_i \cdot e[n] \tag{5.4}$$

where K_i is the integral gain coefficient controlling the adaptation rate.

5.3 Probe #1: Physically Inspired Effects

This first probe is designed to challenge a guitarist's preconceptions about their instrument by evoking sonic characteristics from other culturally and historically distinct string instruments. Across the world, a wide variety of string instruments exist, each embedded in its own performance practices, construction techniques, and cultural significance. These instruments differ not only in their acoustic output but also in the playing techniques, performance contexts, and luthier traditions they embody. Within this rich diversity lies a provocative design opportunity: what happens when sound-contributing features from these instruments are transposed onto an augmented guitar? Though detached from their cultural and physical contexts, these features retain sonic signatures that make them ideal design probes. Can a musician still recognize the source of inspiration purely through sound? Will they intuitively adapt their playing technique in response, or continue interacting with the guitar as they normally would? This probe is intended to prompt reflection and discussion around these questions. To this end, it draws inspiration from two instruments: the banjo and the sitar. The banjo's distinctive sound arises in part from its membrane-based resonator, known as the head, which couples to the strings under tension [54]. Meanwhile, the sitar introduces the concept of sympathetic strings, which are not directly played but instead vibrate in response to the main strings' activity [55]. A sitar typically features up to 21 strings, the majority of which are tuned to resonate with the played pitches (fundamentals plus partials), enriching the sound texture through sympathetic resonance.

In this probe, both elements, the membrane-coupled string interaction and the use of sympathetic strings, are approximated within the guitar's augmented system. It is important to note that the goal is not to achieve a physically accurate emulation, but rather a perceptually recognizable resemblance.

5.3.1 Modal Model of a Membrane

The modes of a circular banjo membrane were computed using the analytical solution to the 2D wave equation in polar coordinates, with boundary conditions enforcing zero displacement at the edge [50]. Modal frequencies correspond to the zeros $j_{d,c}$ of Bessel functions of the first kind J_d, where d is the angular (diametric) and c the radial mode number.

The normalized modal frequencies were scaled by the desired fundamental frequency f_0 using

$$f_{d,c} = f_0 \cdot \frac{j_{d,c}}{j_{0,1}}, \tag{5.5}$$

where $j_{0,1} \approx 2.4048$ is the first zero of J_0. The modal quality factors were defined to increase with the mode index:

$$Q_{d,c} = Q_0 \cdot (1 + \alpha \cdot (d + c + 1)) \,. \tag{5.6}$$

To continuously synthesize the modal response of the membrane to the audio input, each resonance mode was implemented as a second-order recursive filter derived from the difference equation of a damped sinusoidal oscillator [56]. The design uses an exponential decay model, where the pole radius r and angular frequency θ are computed from the modal frequency f_0, quality factor Q, and sampling rate f_s:

$$r = e^{-\pi f_0/(Q f_s)}, \quad \theta = \frac{2\pi f_0}{f_s}. \tag{5.7}$$

The corresponding difference equation is given by:

$$y[n] = 2r\cos(\theta)y[n-1] - r^2 y[n-2] + gx[n], \tag{5.8}$$

where $g = 1 - r$ is a gain normalization factor ensuring consistent energy injection. Each filter simulates a lightly damped resonant mode, and the total output is obtained by summing the responses of all modal filters in parallel.

5.3.2 Waveguides of Sympathetic Strings

The vibrating string was implemented using a digital waveguide model, which simulates bidirectional wave propagation through two delay lines representing left- and right-going traveling waves [56]. The round-trip delay determines the fundamental frequency:

$$f_0 = \frac{f_s}{L}, \tag{5.9}$$

where f_s is the sampling rate and L is the total delay length.
To simulate energy loss, each delay line output is scaled by a damping coefficient $d < 1$. Frequency-dependent dispersion, which models stiffness in real strings (e.g., piano or steel strings), is introduced using a first-order all-pass filter, applied to the wave components before reinjection. This produces a frequency-dependent phase shift, mimicking inharmonic overtones.
Excitation is injected into both delay lines at a configurable position, and the final output is extracted at the bridge location. The final probe uses 17 waveguides, tuned in semitone steps ranging from A2 (110 Hz) to C#4 (277.18 Hz). The modal and waveguide outputs are computed in parallel, so that their interaction is limited to the feedback signal.

5.3.3 Affordances

The effect implementation poses little computational demand on the Daisy Seed, so that the audio processing loop can run with block sizes down to four samples. This places a lower-bound latency of 0.08 ms at a sample rate of 48 000 Hz on the controller. Within DMI research, there seems to be a common understanding that processing delays up to 10 ms do not affect performance accuracy to a strong extent, as long as the jitter, i.e., the variation of latency stays below ±1 ms [57, 58].

These short response times combined with the resonant, slightly reverberating behavior of the effect may incentivize percussive actions, such as rhythmically strumming the strings, while they are held muted. This is a technique in which the effect becomes especially noticeable, as the broadband noise resulting from a forceful strum excites most modes in unison.
As the gain controller allows the gradual build-up of feedback so that a note may be infinitely sustained, the probe may offer a more subtle affordance to a musician. The membrane is tuned to a certain fundamental. Consequently, the feedback will be especially strong when playing notes whose fundamental or first harmonics resonate strongly with the membrane's fundamental or first couple of partial frequencies. Thus, the guitar, an instrument able to play any scale in equal-tempered tuning, may suddenly appear to imply a tuning consisting of the set of notes resonating particularly strongly with the membrane.

5.4 Probe #2: Frequency-domain effect

Performing with audio effects that operate on the frequency-domain representation of a real-time signal can be challenging due to the inherent latency of frame-based operations such as the Fast Fourier Transform (FFT). Especially applications requiring precise tracking of the magnitude and phase information at particular frequencies will require large enough frame sizes to retrieve an appropriate frequency resolution. Given a sample rate of 48 000 Hz, a frame size of 4096 samples yields a bin width of 11.71 Hz. Latency here refers to the time between signal input and the corresponding output becoming available, which would amount to 85 ms.
In a generative application, in which oscillator voices are triggered based on calculations from the frequency domain, such a latency seems prohibitive. Many interesting effects in the frequency domain are imaginable, such as spectral delays or pitch-shifting. So, the question arises how the musician would cope with that delay within an augmented, feedback-controlled instrument.
The implemented effect will control an oscillator bank based on continuous sinusoidal tracking performed in the frequency domain. When a new peak is detected in the magnitude spectrum, it is assigned a unique sinusoidal track ID alongside frequency and magnitude information. Subsequent peaks at that or a close frequency will be associated with the same track to update the information. Using this track information, the oscillator bank can spawn new voices or update existing ones. Tuning the envelope to produce sounds with short attack times will accentuate the presence of a delay.
This probe aims to raise questions about how far this noticeable response time negatively affects the player's ability to engage in expressive phrasing and timing in their playing or whether the presence of a short moment could even be interpreted as a co-performer reacting to the player's own playing. This is expected to yield insights regarding the eligibility of frequency-domain effects in feedback-based actuated instruments.

5.4.1 Implementation

The core effect is implemented in Pure Data[1] running on a computer. Audio communication is achieved via an audio interface and 6.3 millimeter cables. The software running on the Daisy Seed only performs the routing and places the gain controller after the pure data effect output, driving the voice coil actuator.
The sinusoidal tracking is done by the *sigmund*∼ object[2]. Only the tracks output is used which is configured to track the first 18 peaks in the magnitude spectrogram. The actual number of active tracks may be higher, as peaks near a tracked frequency must remain non-dominant for several frames before the track is deleted. The *martha*∼ object[3] created by William Brent processes these tracks and assigns them to oscillator voices with randomized attack, release time, glissando range and duration, and tremolo rate. Sinusoidal tracking just tracks the presence of local maxima in the magnitude spectrogram unaware of the concept of pitch. The frequencies the oscillator bank produces must therefore not always correspond to the notes the player is playing, but could relate to their harmonics or even just noise. The feedback loop additionally distorts this relationship. The slight unrealibilities and unforeseeability of the effect aims to provide the musician with a co-performer, which generally follows the musician's playing but adds nuance and variance to the mix.

5.4.2 Affordances

The effect offers some interesting and new ways to interact with the guitar strings. The infinite sustain here is less dependent on pitch than in the first probe, enabling sustained tones on the higher strings. The A -and low E-string are less easily sustained, likely stemming from the lower relative frequency resolution at lower index frequency bins. For example, the lowest playable subsequent notes E2 at 82.41 Hz and F2 at 87.31 Hz only have a 4.9 Hz distance. Whereas, the same notes played on the high E-string have a 39.2 Hz distance. Due to the logarithmic note-frequency relationship, the frequency resolution effectively breaks down at lower frequencies. Therefore, the frequency the oscillator will output might not be in tune with the fundamental frequency of the played note.
Another unique technique emerged during testing, in which the finger only rests over a fret but damps the string then plugged. This allows the effect to pick up the frequencies related to the fretting position through the short pluck sound that emerges when striking the string. The output of the oscillator will not be damped, producing an interesting hybrid tone, where the transient comes from the string and the sustain from the oscillator. A contrasting effect emerges when playing fast arpeggios, in which the natural output of

[1]Pure Data's website: `https://puredata.info/`
[2]sigmund∼ object documentation: `https://pd.iem.sh/objects/sigmund~/`
[3]martha∼ object: `https://github.com/coderofsalvation/pd-puredata-vanilla-patches/blob/master/williambrent/martha~-help.pd`

the guitar and the synthesizer fuse together. The recurrence of the same or similar set of frequencies will allow the sinusoidal tracks to persist, so that the oscillators stay active for longer. This also increases the feedback over the played strings, leading to a drone-like sound in which the transient of the string becomes less pronounced, but the general timbre of it remains.

Chapter 6

Evaluation

To better understand how the probe implementations affect the relationship between musician and instrument, a qualitative evaluation was conducted with four guitarists. This study serves as a formative investigation, aiming to identify expressive opportunities, challenges, and experiential shifts introduced by the augmented guitar system. Rather than providing a comprehensive or statistical assessment, this study aims to surface initial insights and outline promising directions for future longitudinal research in real-world musical contexts [59].
The evaluation was designed to explore three core questions:

- How do the probes shape or disrupt the musician's sense of control and responsiveness while playing?
- What forms of musical expression and interaction do the probes afford or constrain?
- To what extent do the probes influence the perception of the guitar as a collaborative or autonomous agent?

The design intentions and assumptions behind each probe were discussed in detail in Chapter 5. In summary, Probe #1 draws on physically inspired acoustic elements (membrane coupling and sympathetic resonance) to provoke reflections on instrumental boundaries and cultural associations. Probe #2 uses a frequency-domain processing strategy with perceptible latency to investigate the interpretive framing of the instrument as a co-performer.

6.1 Method

6.1.1 Research Approach

The overall method draws on a phenomenological approach inspired by McMillan and Morreale's work on understanding musician-instrument relationships in accessible DMIs

[45]. This approach emphasizes participants' lived experiences and subjective interpretations. To support this, the study utilized a design probe methodology that encouraged open-ended interaction with the instrument in combination with semi-structured interviews. The merit of this combined method has been outlined in detail in section 2.6.

6.1.2 Participants and Setting

Four guitarists were recruited for individual evaluation sessions. Participants were seated with the instrument and typically demonstrated specific gestures or behaviors directly on the guitar as they reflected on their experience. Each session took place in a quiet environment to foster focus and ease of interaction.

6.1.3 Session Structure

Each session followed a three-part structure:

1. **Initial reflection**: Participants discussed their existing relationship with the guitar and their improvisational practice, and experience in collaborative performance.
2. **Probe interaction**: Both probes were tested in randomized order. After each interaction, participants were asked to reflect on their experience.
3. **Concluding discussion**: A broader conversation was held, focusing on the implications of augmentation and the evolving nature of the musician-instrument relationship.

6.1.4 Interview Design

Semi-structured interviews were conducted to encourage natural conversation. While guided by a predefined set of questions, the interview format was flexible, allowing follow-up questions and thematic digressions based on participant responses. This conversational style allowed for a deeper exploration of subjective experiences and emergent themes.

6.1.5 Data Collection and Ethics

Each session lasted approximately one hour and was audio-recorded for later transcription and analysis. All participants gave informed consent prior to participation, in accordance with ethical research standards.

6.2 Results

Four individuals participated in this study, all of whom have a sustained personal or professional relationship with the guitar. The sample was intentionally diverse in terms of musical background, level of formal training, and performance experience, to capture a broad range of perspectives on improvisation and interaction with the design probes.

6.2.1 Participants

Given the small sample size, each participant is briefly introduced to contextualize their responses and musical orientation.
Participant 1 is an experienced guitarist with over 15 years of playing history, including extensive work in bands focused on rock, blues, and funk genres. Although proficient in classical, acoustic, and electric guitar, Participant 1 primarily plays a Gibson electric. Improvisation is central to their practice, serving both as a means of emotional expression and a core artistic objective. They emphasize the importance of listening and mutual responsiveness during group improvisation.
Participant 2 transitioned from bass and double bass to electric guitar and has 5–10 years of solo playing experience. Their approach is theory-driven, using improvisation as a tool for compositional ideation. Effects processing is integral to their sound design.
Participant 3 is a casual, self-taught guitarist whose practice is primarily exploratory and tactile. With no formal training or performance goals, they focus on timbral discovery. Their musical interests have more recently shifted toward synthesizers and electronic instruments.
Participant 4 is a professional guitarist with over a decade of international performance, recording, and production experience. They are trained in both guitar and classical piano. Improvisation is regarded as an embodied, socially responsive act unfolding through iterative exploration.

6.2.2 Thematic Analysis

Two major themes emerged across participant responses: (1) a shift in perceived control and the embrace of uncertainty, and (2) a perspective on the instrument as a collaborative agent.

Redefining Control and Embracing Uncertainty

All participants reported a change in the sense of control while interacting with the probes. Rather than perceiving this lack of control as a limitation, many framed it as an opportunity for curiosity, skill acquisition, and rationalization of the instrument's behavior:

> "[I am] not feeling that I'm a hundred percent both understanding and in control of it, [...] but for me, that's more driving curiosity."

> "I could be more expressive with it. Like knowing when the feedback hits. At the moment, I'm still waiting, and a little bit too late."

> "Maybe I can get it to resonate. Maybe I have to plug it harder. [...] You wrap [your head] around what the [instrument's] body gives you."

Some participants actively developed playing strategies to navigate this uncertainty. For instance, one participant varied their fretting pressure to modulate the amplitude of an infinitely sustained tone on Probe #1. Others adapted harmonic excitation techniques using Probe #2's oscillator voices, enabling clearer harmonic string resonance even when the string was damped due to the traditional technique.
Additionally, two participants explored a technique in which a sustained note was held while other fingers played a melody. One participant executed this with a high degree of control, describing how the sustained note gained prominence dynamically, timbrally, and harmonically, acting as an anchor around which the melody revolved.

The Guitar as a Collaborator

Two participants explicitly described their experience with Probe #2 as analogous to performing with a bandmate:

> "It felt like something, your co-performer or bandmates would do."

> "It was like playing with a band, but without playing with a band."

This perception appeared connected to the system's musical agency. One participant described a kind of empathy for the system, noting that while its output sometimes deviated from their expectations, it remained musically valid:

> "I see where [the instrument] went and it's not the wrong choice... but a choice I didn't expect."

Another reflected on a blurred boundary of authorship:

> "It's like somebody else doing it, but guess what? It was me all along."

These experiences also influenced creative flow. Participants noted the effect of the system's response on their attention and vocal habits:

> "For the creative part, I think I would use it to create a different environment, different ambient, different sensation as well."

> "When I usually play the acoustic guitar, I am either singing or vocalizing along. So I'm adding something to the playing... and here, I didn't have the need to sing. [...] Having this meditative conversation."

6.2.3 Revisiting Design Assumptions

Probe #1: Physically Inspired Effects

Probe #1 aimed to prompt reflection on the boundaries between related instruments by mimicking features of the banjo and sitar. One participant immediately associated the sound with a banjo and responded by playing closer to the bridge to enhance the metallic tone. They also noted variation across the string set: higher strings produced a distinct "banjo" effect, while lower ones resembled reverb.
Other participants did not recognize specific acoustic references, instead describing the effect in metaphorical or functional terms such as “shimmery” or similar to amplifier reverb. For most, the effect did not appear to alter their connection to the guitar significantly.
While all participants noted the probe’s note-dependent behavior, only two explored which notes sustained and resonated most strongly. Both identified G3 on the D string as especially responsive. This aligns with the membrane’s modal model, tuned to 200 Hz, which lies between G3 and G#3.
Overall, the probe achieved only partial success in evoking associations with other instruments. Most participants did not reference the cultural or acoustic origins of the effect, suggesting that the intended disruptive quality remained subtle or unrecognized.

Probe #2: Frequency-Domain Effect

Probe #2 deliberately introduced latency through frequency-domain processing, making this a core design feature. Participants perceived this latency not as computational delay but as a musical effect, describing it as “dreamy,” “radiant,” or “creepy.”
Although participants did not explicitly connect latency to the instrument’s musical agency, the combination of delay and randomized oscillator behavior appeared to support the perception of the guitar as a responsive or semi-autonomous co-performer.
Probe #2 prompted a range of expressive techniques, including:

- Sustained vibrato modulation, allowing dynamic timbral shifts without additional energy input.
- Muting techniques to shape the oscillator output, allowing it to pick up the frequencies of the unmuted tone, but also percussive frequencies caused by the quick muting action.
- More reliable harmonic playing, enhancing expression.
- Emphasizing individual, randomly reinforced resonances while strumming a chord.

These findings generally align with the design hypotheses. Participants adapted to the effect’s behavior, and the latency did not hinder, but often enriched, expressive play, even giving the impression of a collaborator.

6.3 Discussion

6.3.1 Reflections on the Evaluation Method

The design probe methodology enabled rich musical discussions, particularly concerning participants' evolving relationships with the instrument. Rather than focusing on the probes as technological artifacts, the evaluation facilitated reflection on broader questions of control, responsiveness, and expression in performance.
However, the results must be interpreted with caution. This evaluation was limited to first impressions—sessions lasted approximately one hour, with 30 to 40 minutes of hands-on interaction. While some participants reported early signs of skill acquisition and understanding, the short duration did not allow for deep learning, discovery of expressive limitations, or long-term adaptation. The findings presented here are thus best considered open-ended and formative.
This aligns with the intention of the study as a probe-driven exploration. The notion of the research product as defined by Jack et al. [42], a near-product-quality artifact deployed for open-ended exploration, offers a useful frame for how these tools could evolve.

6.3.2 Expressive Potential and Design Implications

The evaluation revealed that the design space for actively controlled or self-resonating guitars remains largely unexplored, particularly for traditional guitarists. All participants identified expressive opportunities in their interactions with the probes. The two designs supported distinct musical behaviors and aesthetics, suggesting that varied combinations of feedback-based control strategies and audio effects could enable a wide range of future instruments.
Participants' responses also reflected differing creative workflows. Some viewed the probes as a tool to refine pre-existing musical intentions, while others adapted their playing in response to the instrument's behavior. This mirrors how guitarists approach effect pedals, either as extensions of an idea or as inspiration and starting point for new musical material.
These parallels point to a design opportunity: enabling players to construct and manipulate the feedback path themselves. Given guitarists' familiarity with building pedal chains, exposing similar parameters, such as effect type, routing, or RMS control settings, could feel natural. This would not only enhance expressivity but reframe common tools by placing them within a feedback loop, potentially giving them a second, dynamic role in shaping the instrument's sound.

6.3.3 Directions for Research Products

Two trajectories emerge for how future research products could build on the insights from this study.

The first is closely aligned to the guitar's history: treating the guitar augmentations as an extension of the traditional instrument, offering new affordances. In this mode, guitarists could customize the feedback path as they would their effect pedal combination, tuning their instrument's self-resonance to match expressive needs. This path integrates seamlessly with familiar workflows and could accelerate adoption among traditional players. Similarly to how Newton and Marshall provided guitarists with simple means to experiment with guitar augmentations(e.g., simplified, solder-less sensors and a toolbox for designing mappings), guitarists would be enabled to customize the effects easily. For the observing researcher, this opens a window into their thought processes during creation and experimentation, creating many different probes as a side-effect [60].
The second is a more transformational path: embracing the complexity and unpredictability of self-resonant behavior as a defining characteristic of a new instrument. In this view, the system is not merely augmenting an existing instrument but creating its own identity and aesthetic. Here, the concept of musical agency, where the instrument contributes semi-autonomously to the performance, becomes central.
The Halldorophone is a prominent example of this approach [16]. While inspired by the cello, the instrument has developed a distinct trajectory rooted in its feedback dynamics. Rather than emulating cello behavior, it deepens its path on self-resonance as a central expressive element. Over more than a decade of artistic deployment, the Halldorophone has led to new understandings not only of itself but of broader themes such as control, authorship, and collaboration in music. A similar path may be possible for the actively controlled guitar, should future iterations intentionally cultivate and shape this autonomous behavior.

Chapter 7

Conclusion

This thesis pursued two main objectives:

1. To evaluate the feasibility of using current-sensing amplifiers with a voice coil actuator as a collocated sensor/actuator pair for actively controlling the vibrations of an acoustic guitar, particularly at the string level.
2. To explore how active control technologies might shape or transform the performer-instrument relationship.

7.1 Final Remarks

This work makes the following contributions:

1. A low-latency, collocated actuator system based on the Daisy Seed platform, capable of self-sensing actuation and tailored for active vibrational control.
2. Two design probes that investigate physically and temporally disruptive feedback mechanisms within guitar augmentation.
3. A qualitative evaluation of augmented guitar performance, highlighting the expressive and cognitive effects of embodied disruption.

7.1.1 Validation of the Control System

The implemented control system successfully demonstrated its ability to damp selected structural resonances of the guitar body when excited percussively. However, attempts to control string vibrations were unsuccessful due to the system's low signal-to-noise ratio in sensing string motion. This limitation, likely rooted in the asymmetric mechanical impedances between actuation and sensing, rendered the setup inadequate for fine-grained string control as originally intended.

Nevertheless, the design retains potential value for other domains. Its compact, self-sensing configuration, relying on a single off-the-shelf actuator and low-latency embedded processing, may offer advantages in structural control for non-stringed instruments, for example, drums. In line with prior work by Davison et al. [61], the system could enable novel interactions with physical modeling synthesis in haptic interfaces, particularly where feedback cancellation is desirable.

7.1.2 Effects on Performer-Instrument Relationship

Despite technical limitations, deploying the control system with some adaptations in a full-scale augmented guitar yielded rich insights. Guitarists responded with notable curiosity and engagement. Many described the instrument as challenging yet rewarding, provoking new techniques and performance strategies. For some, it shifted their musical mindset, fostering experiences described as collaborative, improvisational, or even meditative.

The design probe methodology proved effective in eliciting these responses. By intentionally disrupting established performer-instrument dynamics, the probes facilitated a reflective and exploratory interaction. While the small number of participants limits the generalizability of results, the depth of qualitative feedback supports the potential of such augmentations and justifies further longitudinal research.

7.2 Future Work

Compared to other areas within the NIME community, the field of active control in acoustic instruments remains underexplored. The technical complexity of real-time feedback control may present a barrier. Yet, as this work suggests, the creative and expressive potential of these instruments warrants deeper investigation.

Future research should prioritize the development of simplified, reproducible setups for active control. This could involve foundational work in sensor-actuator design or the creation of accessible toolkits that abstract away low-level implementation details. Such systems would empower more musicians and researchers to explore the expressive affordances of actuated instruments.

Given an accessible hardware platform, larger-scale evaluations could be conducted by distributing DIY kits to guitarists. Drawing on the familiarity many musicians already have with effect pedals, future designs might allow performers to route these effects into the feedback path, while the system automatically manages gain to prevent instability. Such systems would not only enable new sonic possibilities but also preserve the tactile and performative qualities that define the guitar.

In the spirit of cultural probes, this participatory, open-ended exploration could serve as a catalyst for broader reflection on how digital augmentation reshapes the guitar. Ultimately, this thesis advocates for a view of augmentation not merely as a technical enhancement, but as an invitation to reimagine the musician-instrument relationship itself.

Bibliography

[1] Matthew Davison et al. "A Self-Sensing Haptic Actuator for Tactile Interaction with Physical Modelling Synthesis". en. In: ().

[2] Otso Lähdeoja. "An Approach to Instrument Augmentation!: the Electric Guitar". en. In: (2008).

[3] Steven Fulton Griffin. "Acoustic replication in smart structures using active structural/acoustic control". English. Ph.D. United States – Georgia: Georgia Institute of Technology, 1995. ISBN: 9798208847176. URL: https://www.proquest.com/docview/304190581/abstract/79EF5863D9D64C65PQ/1.

[4] Simon Benacchio et al. "Modal proportional and derivative state active control applied to a simplified string instrument". en. In: *Journal of Vibration and Control* 22.18 (Oct. 2016), pp. 3877–3888. ISSN: 1077-5463, 1741-2986. DOI: 10.1177/1077546314566440.

[5] Steve Griffin, Steven A. Lane, and Robert L. Clark. "The application of smart structures toward feedback suppression in amplified acoustic guitars". en. In: *The Journal of the Acoustical Society of America* 113.6 (June 2003), pp. 3188–3196. ISSN: 0001-4966, 1520-8524. DOI: 10.1121/1.1562649.

[6] Marcelo Mortensen Wanderley and Nicola Orio. "Evaluation of input devices for musical expression: Borrowing tools from HCI". In: *Computer Music Journal* 26.3 (2002), pp. 62–76.

[7] Loïc Reboursière et al. "Multimodal Guitar: A Toolbox For Augmented Guitar Performances." In: *NIME*. 2010, pp. 415–418. URL: https://www.academia.edu/download/77115798/nime2010_415.pdf.

[8] Duncan MacConnell, Shawn Trail, and George Tzanetakis. "Reconfigurable Autonomous Novel Guitar Effects (RANGE)". en. In: (2013).

[9] Oliver Hödl and Geraldine Fitzpatrick. "Exploring the design space of hand-controlled guitar effects for live music". In: *ICMC*. 2013. URL: https://www.researchgate.net/profile/Oliver-Hoedl/publication/262178423_Exploring_the_Design_Space_of_Hand-Controlled_Guitar_Effects_for_Live_Music/links/0f317536ce57cce08b000000/

Exploring-the-Design-Space-of-Hand-Controlled-Guitar-Effects-for-Live-Music.pdf.

[10] Eduardo A L Meneses, Sérgio Freire, and Marcelo M Wanderley. "GuitarAMI and GuiaRT: two independent yet complementary Augmented Nylon Guitar projects". en. In: ().

[11] Juan Pablo Martinez Avila et al. "Augmenting Guitars for Performance Preparation". In: *Proceedings of the 14th International Audio Mostly Conference: A Journey in Sound*. AM '19. New York, NY, USA: Association for Computing Machinery, Sept. 2019, pp. 69–75. ISBN: 978-1-4503-7297-8. DOI: 10.1145/3356590.3356602. URL: https://dl.acm.org/doi/10.1145/3356590.3356602.

[12] Dan Overholt, Edgar Berdahl, and Robert Hamilton. "Advancements in Actuated Musical Instruments". English. In: *Organised Sound* 16.2 (Aug. 2011), pp. 154–165. ISSN: 13557718. DOI: 10.1017/S1355771811000100.

[13] Otso Lähdeoja. "An Augmented Guitar With Active Acoustics". In: *Proceedings of the Sound and Music Computing Conferences.* publisher: Zenodo. Maynooth, Co. Kildare, Ireland.: Zenodo, July 2015. ISBN: 9780992746629. DOI: 10.5281/ZENODO.851049. URL: https://zenodo.org/record/851049.

[14] Charles Besnainou. "Transforming the voice of musical instruments by active control of the sound radiation". In: *INTER-NOISE and NOISE-CON Congress and Conference Proceedings* 1999.5 (Dec. 1999), pp. 1317–1321.

[15] Jiffer Harriman. "Feedback Lap Steel: Exploring Tactile Transducers as String Actuators". en. In: (2015).

[16] Halldór Úlfarsson. "The halldorophone: The ongoing innovation of a cello-like drone instrument". en-US. In: 2018, pp. 269–274. ISBN: 978-1-949373-99-8. DOI: 10.5281/zenodo.1302579. URL: https://www.nime.org/proc/ulfarsson2018/.

[17] S.J. Elliott and P.A. Nelson. "The active control of sound". en. In: *Electronics Communications Engineering Journal* 2.4 (1990), p. 127. ISSN: 09540695. DOI: 10.1049/ecej:19900032.

[18] Edgar Berdahl, Günter Niemeyer, and JO Smith. *Feedback control of acoustic musical instruments*. Tech. rep. Technical Report STAN-M-120. Palo Alto, California: Stanford University, 2008.

[19] Edgar Berdahl and Julius O Smith. "Some Physical Audio Effects". en. In: *Proc. of the 9th Int. Conference on Digital Audio Effects (DAFx-06)*. Montreal, Canada, 2006.

[20] Luca Turchet. "Smart Musical Instruments: Vision, Design Principles, and Future Directions". In: *IEEE Access* 7 (2019), pp. 8944–8963. ISSN: 2169-3536. DOI: 10.1109/ACCESS.2018.2876891.

[21] Luca Turchet. “Some reflections on the relation between augmented and smart musical instruments”. In: *Proceedings of the Audio Mostly 2018 on Sound in Immersion and Emotion*. AM ’18. New York, NY, USA: Association for Computing Machinery, Sept. 2018, pp. 1–7. ISBN: 978-1-4503-6609-0. DOI: 10.1145/3243274.3243281. URL: https://dl.acm.org/doi/10.1145/3243274.3243281.

[22] Luca Turchet, Andrew McPherson, and Carlo Fischione. “Smart Instruments: Towards an Ecosystem of Interoperable Devices Connecting Performers and Audiences”. eng. In: Hambourg, 2016. ISBN: 978-3-00-053700-4. URL: https://iris.unitn.it/handle/11572/226231.

[23] Nicolas Bouillot et al. “A Mobile Wireless Augmented Guitar.” In: *NIME*. 2008, pp. 189–192. URL: https://www.academia.edu/download/30512237/10.1.1.140.3830.pdf#page=207.

[24] T. T. Soong. “State-of-the-art review: Active structural control in civil engineering”. In: *Engineering Structures* 10.2 (Apr. 1988), pp. 74–84. ISSN: 0141-0296. DOI: 10.1016/0141-0296(88)90033-8.

[25] Edgar Berdahl, Julius O. Smith, and Günter Niemeyer. “Feedback control of acoustic musical instruments: Collocated control using physical analogs”. en. In: *The Journal of the Acoustical Society of America* 131.1 (Jan. 2012), pp. 963–973. ISSN: 0001-4966, 1520-8524. DOI: 10.1121/1.3651091.

[26] Edgar Berdahl, J. O. Smith, and Adrian Freed. “Active damping of a vibrating string”. In: *Active, Adelaide, Australia* (2006). URL: https://ccrma.stanford.edu/~eberdahl/Papers/Active2006BerdahlSmith.pdf.

[27] Liam Donovan. “Travelling Wave Control of Stringed Musical Instruments”. en. Accepted: 2019-01-03T15:12:36Z. Thesis. Queen Mary University of London, Nov. 2018. URL: https://qmro.qmul.ac.uk/xmlui/handle/123456789/54052.

[28] Simon Benacchio et al. “Mode tuning of a simplified string instrument using time-dimensionless state-derivative control”. In: *Journal of Sound and Vibration* 334 (Jan. 2015), pp. 178–189. ISSN: 0022-460X. DOI: 10.1016/j.jsv.2014.09.003.

[29] Simon Benacchio et al. “Combined state and state derivative control applied to musical string instruments”. en. In: Montreal, Canada, 2013, pp. 065066–065066. DOI: 10.1121/1.4800112. URL: https://pubs.aip.org/asa/poma/article/959869.

[30] Henri Boutin and Charles Besnainou. “Physical parameters of an oscillator changed by active control. Application to the xylophone bar.” In: *DAFx08*. 2008. URL: https://hal.science/hal-02470046/.

[31] Thibaut Meurisse et al. “Experimental Demonstration of the Modification of the Resonances of a Simplified Self-Sustained Wind Instrument Through Modal Active Control”. en. In: *Acta Acustica united with Acustica* 101.3 (May 2015), pp. 581–593. ISSN: 16101928. DOI: 10.3813/AAA.918854.

[32] Henri Boutin and Charles Besnainou. "A modal method adapted to the active control of a xylophone bar". In: *Acoustics 2012*. 2012. URL: https://hal.science/hal-03583419/document.

[33] S. Fels. "Designing for intimacy: creating new interfaces for musical expression". In: *Proceedings of the IEEE* 92.4 (Apr. 2004), pp. 672–685. ISSN: 1558-2256. DOI: 10.1109/JPROC.2004.825887.

[34] F. Richard Moore. "The Dysfunctions of MIDI". In: *Computer Music Journal* 12.1 (1988), pp. 19–28. ISSN: 0148-9267. DOI: 10.2307/3679834.

[35] Luc Nijs, Micheline Lesaffre, and Marc Leman. "The musical instrument as a natural extension of the musician". In: *Proceedings of the 5th Conference of Interdisciplinary Musicology*. LAM-Institut jean Le Rond d'Alembert Paris, 2009, pp. 132–133. URL: https://www.academia.edu/download/51458110/The_musical_instrument_as_a_natural_exte20170121-6580-pdl7q1.pdf.

[36] Perry R. Cook. "Remutualizing the Musical Instrument: Co-Design of Synthesis Algorithms and Controllers". en. In: *Journal of New Music Research* 33.3 (Sept. 2004), pp. 315–320. ISSN: 0929-8215, 1744-5027. DOI: 10.1080/0929821042000317877.

[37] Filipe Calegario. "Challenges in Designing DMIs". en. In: *Designing Digital Musical Instruments Using Probatio: A Physical Prototyping Toolkit*. Ed. by Filipe Calegario. Cham: Springer International Publishing, 2019, pp. 5–17. ISBN: 978-3-030-02892-3. DOI: 10.1007/978-3-030-02892-3_2. URL: https://doi.org/10.1007/978-3-030-02892-3_2.

[38] Thor Magnusson and Enrike Hurtado Mendieta. "The acoustic, the digital and the body: a survey on musical instruments". en. In: *Proceedings of the 7th international conference on New interfaces for musical expression - NIME '07*. New York, New York: ACM Press, 2007, p. 94. DOI: 10.1145/1279740.1279757. URL: http://portal.acm.org/citation.cfm?doid=1279740.1279757.

[39] Simon Waters. "The entanglements which make instruments musical: Rediscovering sociality". In: *Journal of New Music Research* 50.2 (Mar. 2021), pp. 133–146. ISSN: 0929-8215. DOI: 10.1080/09298215.2021.1899247.

[40] Chiara Rossitto et al. "Musicians' initial encounters with a smart guitar". en. In: *Proceedings of the 10th Nordic Conference on Human-Computer Interaction*. Oslo Norway: ACM, Sept. 2018, pp. 13–24. ISBN: 978-1-4503-6437-9. DOI: 10.1145/3240167.3240223. URL: https://dl.acm.org/doi/10.1145/3240167.3240223.

[41] Bill Gaver, Tony Dunne, and Elena Pacenti. "Design: Cultural probes". en. In: *Interactions* 6.1 (Jan. 1999), pp. 21–29. ISSN: 1072-5520, 1558-3449. DOI: 10.1145/291224.291235.

[42] Robert Jack, Jacob Harrison, and Andrew McPherson. "Digital Musical Instruments as Research Products". en-US. In: 2020, pp. 446–451. DOI: 10.5281/zenodo.4813465. URL: https://www.nime.org/proc/nime20_86/.

[43] Kirsten Boehner et al. "How HCI interprets the probes". en. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. San Jose California USA: ACM, Apr. 2007, pp. 1077–1086. ISBN: 978-1-59593-593-9. DOI: 10.1145/1240624.1240789. URL: https://dl.acm.org/doi/10.1145/1240624.1240789.

[44] Koray Tahıroğlu et al. "Digital Musical Instruments as Probes: How computation changes the mode-of-being of musical instruments". en. In: *Organised Sound* 25.1 (Apr. 2020), pp. 64–74. ISSN: 1355-7718, 1469-8153. DOI: 10.1017/S1355771819000475.

[45] Andrew McMillan and Fabio Morreale. "Designing accessible musical instruments by addressing musician-instrument relationships". English. In: *Frontiers in Computer Science* 5 (May 2023). ISSN: 2624-9898. DOI: 10.3389/fcomp.2023.1153232. URL: https://www.frontiersin.org/journals/computer-science/articles/10.3389/fcomp.2023.1153232/full.

[46] *Max98389 Datasheet*. en. URL: https://www.analog.com/media/en/technical-documentation/data-sheets/max98388-max98389.pdf.

[47] Richard Mark French. "Physics of Acoustic Guitars". en. In: *Acoustic Guitar Design*. Springer, Cham, 2022, pp. 197–231. ISBN: 978-3-030-89381-1. DOI: 10.1007/978-3-030-89381-1_5. URL: https://link.springer.com/chapter/10.1007/978-3-030-89381-1_5.

[48] P. Welch. "The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms". en. In: *IEEE Transactions on Audio and Electroacoustics* 15.2 (June 1967), pp. 70–73. ISSN: 0018-9278. DOI: 10.1109/TAU.1967.1161901.

[49] Matti Karjalainen et al. "Perception of temporal decay of low-frequency room modes". In: *Proceedings of the 116th Audio Engineering Society Convention, Berlin, Germany*. 2004. URL: https://www.aes.org/e-lib/download.cfm?ID=12752.

[50] Antoine Chaigne and Jean Kergomard. *Acoustics of Musical Instruments*. Modern Acoustics and Signal Processing. New York, NY: Springer New York, 2016. ISBN: 978-1-4939-3677-9. DOI: 10.1007/978-1-4939-3679-3. URL: http://link.springer.com/10.1007/978-1-4939-3679-3.

[51] Myles Cameron Nadarajah. "The mechanics of the soundpost in the violin". en. In: (July 2019). DOI: 10.17863/CAM.41177. URL: https://www.repository.cam.ac.uk/handle/1810/294077.

[52] Antonin Novak et al. "Guitar Pickup: Measurement of its Two-Dimensional Nonlinear Function". en. In: *Journal of the Audio Engineering Society* 68.3 (Mar. 2020), pp. 184–192. ISSN: 15494950. DOI: 10.17743/jaes.2020.0002.

[53] Edgar Berdahl and Julius O. Smith. "Inducing Unusual Dynamics in Acoustic Musical Instruments". In: *2007 IEEE International Conference on Control Applications*. Oct. 2007, pp. 1336–1341. DOI: 10.1109/CCA.2007.4389421. URL: https://ieeexplore.ieee.org/document/4389421/?arnumber=4389421.

[54] Jim Woodhouse, David Politzer, and Hossein Mansour. "Acoustics of the banjo: measurements and sound synthesis". en. In: *Acta Acustica* 5 (2021), p. 15. ISSN: 2681-4617. DOI: 10.1051/aacus/2021009.

[55] David Ronan and Mr Giuseppe Torre. "The physical modelling of a sitar". PhD Thesis. Master's thesis, University of Limerick, Limerick, Ireland, 2010. URL: http://issta.ie/wp-content/uploads/The-Physical-Modelling-of-a-Sitar.pdf.

[56] Julius O. Smith. *Physical Audio Signal Processing*. online book, 2010 edition. http://ccrma.stanford.edu/~jos/pasp/, accessed May 2025.

[57] David Wessel and Matthew Wright. "Problems and prospects for intimate musical control of computers". In: *Computer music journal* 26.3 (2002), pp. 11–22.

[58] Robert H. Jack, Tony Stockman, and Andrew McPherson. "Effect of latency on performer interaction and subjective quality assessment of a digital musical instrument". en. In: *Proceedings of the Audio Mostly 2016*. Norrköping Sweden: ACM, Oct. 2016, pp. 116–123. ISBN: 978-1-4503-4822-5. DOI: 10.1145/2986416.2986428. URL: https://dl.acm.org/doi/10.1145/2986416.2986428.

[59] Carol M. Barnum. *Usability testing essentials: Ready, set... test!* Morgan Kaufmann, 2020. URL: https://books.google.com/books?hl=de&lr=&id=L6_SDwAAQBAJ&oi=fnd&pg=PP1&dq=Usability+Testing+Essentials&ots=kBeNM5x4va&sig=9HRBpbJnfcRHd8EnCwOGAQ3pL1E.

[60] Dan Newton and Mark T. Marshall. "Examining How Musicians Create Augmented Musical Instruments". en-US. In: 2011, pp. 155–160. DOI: 10.5281/zenodo.1178121. URL: https://nime.org/proc/newton2011/index.html.

[61] Matthew Davison, Anna Silver, and Andrew P McPherson. "Self-Sensing Transducers for Tactile Interaction with Digital Musical Instruments". en. In: ().

Appendix A

PCB schematic

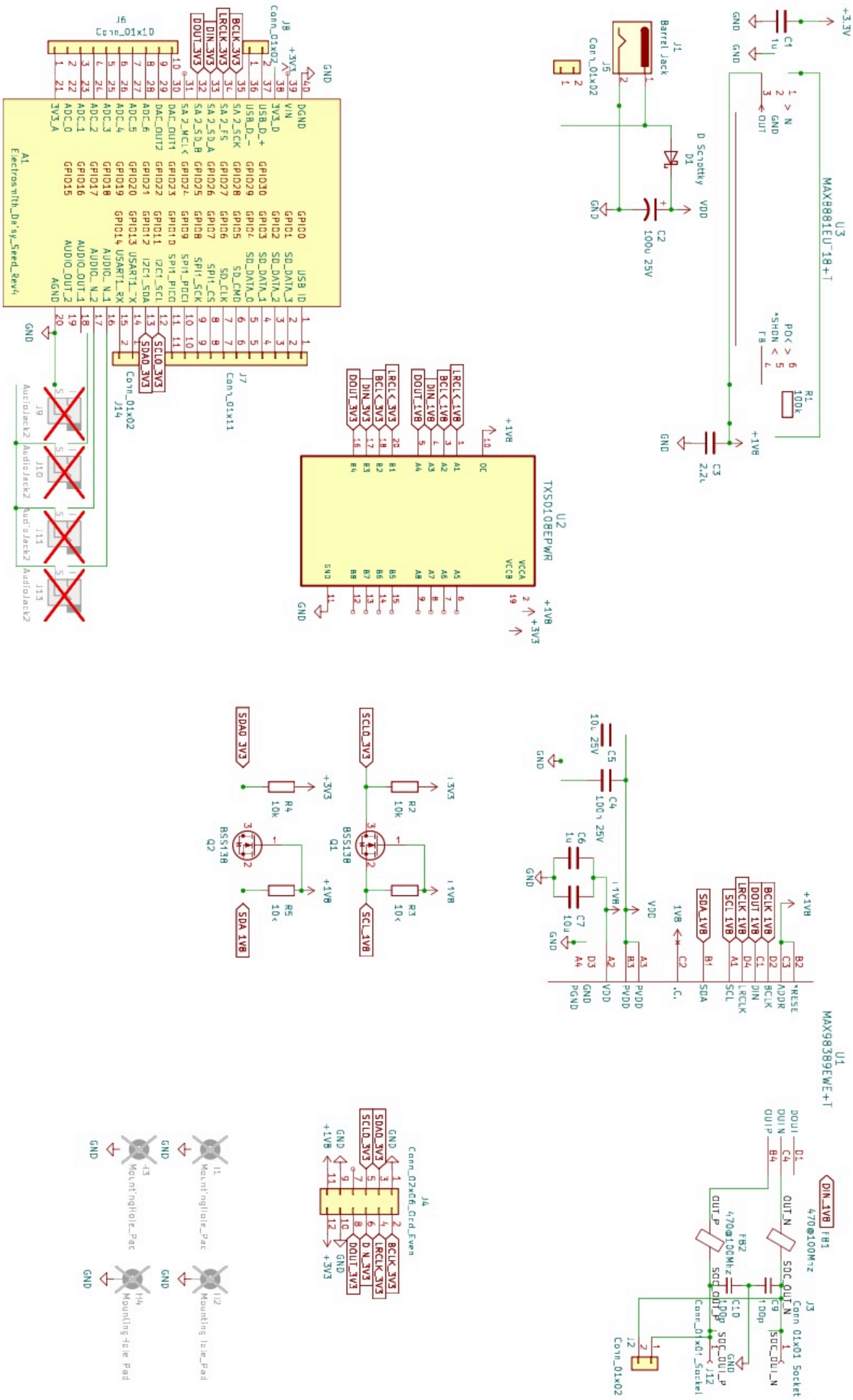


Figure A.1: Schematic of the control system PCB

Appendix B

Evaluation material

B.1 Guiding questions

These questions guided the discussion.

B.1.1 Initial questions

1. What kind of guitar do you usually play?
2. In what contexts do you play the guitar?
3. How would you describe your relationship with the guitar - is it expressive, intuitive, resistant, inspiring?
4. Do you use any effects? What for? (Sonic identity, creative inspiration, etc.)
5. What role does improvisation play for you?

B.1.2 Questions after each probe

How did you intuitively understand or control what the instrument was doing?

1. Were there moments where it "made sense" to you musically?
2. How does it compare to your prior improvisation experience?
3. Did anything feel unpredictable or confusing?

What physical actions or gestures felt most effective or musically rewarding?

1. Were there things you found yourself doing naturally?
2. Did it feel like you could “learn” the instrument as you went?

Did your connection to this instrument feel different from a traditional guitar?

1. In what ways did it feel similar, and in what ways different?

How did the instrument's response affect your timing, phrasing, or expression?

1. Were you adapting to the instrument, or was it adapting to you?

Did you ever find yourself playing something unexpected or surprising?

1. What do you think led to that?

B.1.3 Questions after both probes

1. Between the two probes, which one felt more musically engaging — and why?
2. Which probe felt more like a musical partner or collaborator?
3. Can you imagine either of these instruments fitting into your practice or performance?
4. Did either of the instruments change how you think about your guitar or your playing?

B.2 Quotes related to the thematic analysis

These are further quotes attributed to the discovered themes.

B.2.1 The Guitar as a Collaborator

Co-performance "It felt like something, your co-performer or bandmates would do." (participant 3) "It was like playing with a band, but without playing with a band." (participant 4) **Musical agency** "I see where [the instrument] went and it's not the wrong choice... but a choice I didn't expect." (participant 4) " [...] it's like somebody else doing it, but guess what? It was me all along." (participant 3) "There's a difference between playing a guitar and playing with a guitar." (participant 4)

B.2.2 Redefining Control and Embracing Uncertainty

Uncertainty, Loss of Control, and Curiosity "[I am] not feeling that I'm a hundred percent both understanding and in control of it, [...] but for me, that's more driving curiosity" (participant 3)
"I don't think that I feel powerless. It's like when you get a new effect pedal, you have no idea how to control it [initially]" (participant 4)

"I could be more expressive with it. Like knowing when the feedback hits. At the moment I'm still waiting and a little bit too late." (participant 2)
"Maybe I can get it to resonate. Maybe I have to plug it harder. [...] You wrap [your head] around what the body gives you" (participant 4)
"It's not so easy to control it." (participant 1)
Gesture and Technique Reimagined "I press, I release and, and the guitar is still actually playing. [The pressing and releasing] is like a volume [modulation]. " (participant 1) "I was muting more to kind of stop that sustain coming through and also playing more staccato-y stuff" (participant 2) "I was kind of hoping, oh, I can play some stuff over the sustained note, but I'm not good enough to do that" (participant 2)

B.2.3 Mindfulness and Expressive Play

"When I usually play the acoustic guitar I am either singing or vocalizing along. So I'm adding something to the playing on the acoustic guitar and here, I didn't have the need to sing. It's more like oh this is a cool chord, I can play around with that and make it resonate. Having this meditative conversation." (participant 4) "For the creative part, I think I would use it to create a different environment, different ambient, different sensation as well. " (participant 1)

Appendix C

Other resources

The source code, design files, and other relevant files can be found at
`https://github.com/moewe-audio/actuated-active-guitar-project`
A demonstration video has been uploaded to the internet at:
`https://www.youtube.com/watch?v=xpIey78m064`