CHELYS SONORUM: A QUASI-AUTONOMOUS GUITAR

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ABSTRACT

Chelys Sonorum is a hybrid electroacoustic guitar that combines hexaphonic electromagnetic sustain and motorized string-tension control to investigate quasi-autonomous sound production. Each string integrates an independent pickup-exciter pair for sustained self-resonance, while six geared DC motors adjust tuning in real time via *Arduino* and a *Max* control patch. A control pipeline based on loudness, pitch, and spectral descriptors modulates feedback response and an auto-tuning system during operation. The paper documents the design of the instrument and reports on its deployment in the installation *I've Used to Play It*, presented at the To Listen To 2025 festival in Turin, as a case study of long-duration operation in a public installation context. In this setting, a database of popular music riffs was used to destabilize the feedback and to force transitions. The installation demonstrated robust long-duration operation with limited technical intervention, while also revealing limitations in chroma-based analysis under feedback-driven conditions.

1. INTRODUCTION

Since the mid-20th century, the electric guitar has become a privileged site for experiments in feedback, augmentation, and robotic control. In these contexts, the instrument is no longer understood as a passive sound source, but as a dynamic system in which material properties, signal processing, actuation, and performance conditions interact.

1.1 Guitar and Sustain

The use of feedback as a compositional and performative tool dates back to the late 1960s, with works such as David Behrman's *Wave Train*, Alvin Lucier's *I am sitting in a Room*, and Gordon Mumma's *Hornpipe*. Guitarists including Jimi Hendrix, Glenn Branca, and Robert Fripp explored the expressive potential of feedback, transforming the electric guitar into an instrument of interaction between body, amplification, and space. A remarkable contribution came from Nicolas Collins's *Backwards Electric Guitar* [1], which reconceived the instrument as a resonant system in which external signals were reinjected into the strings to trigger electromagnetically driven vibrations.

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These experiments, situated between sound art and experimental lutherie, anticipated many of today's central questions regarding hybrid instruments and self-listening systems.

The principle of infinite *sustain* in string instruments is now well established in both artistic and commercial contexts. Notable examples include Andrew McPherson's *Magnetic Resonator Piano* [2] and Halldór Úlfarsson's *halldorophone* [3]; in the guitar domain, electromagnetic sustain has been implemented in devices such as the *E-Bow* [4], the *Fernandes Sustainer*, and *Sustainiac*, as well as in more complex instruments such as the *Moog Guitar* and the *Roland GS-500*. In sound installation, works such as Agostino Di Scipio's *Modi di Interferenza* [5] and Alvin Lucier's *Music on a Long Thin Wire* [6] further established paradigms in which the instrument listens to and modulates itself.

1.2 Guitar and Robotics

In recent years, the electric guitar has also become a fertile ground for robotic and augmented approaches, where the focus shifts from playing alone to the negotiation of roles among composer, inventor, performer, and machine. These approaches reveal distributed forms of control, from corpus-based methods that use audio descriptors to shape feedback trajectories in the guitar-amplifier system [7], to the *Talking Guitar*, which uses headstock tracking and mapping strategies to question the intuitiveness of embodied interaction [8].

Robotic systems such as *StrumBot* extend expressive techniques including vibrato, muting, and bending through mechatronic control [9, 10]. Other guitar augmentation projects combine sensors, hexaphonic pickups, and actuation/analysis systems to generate co-performative presences and multimodal forms of control [11]. Within this framework, the question is no longer simply who is playing, but who determines what can be played, when, and how; composition becomes system-specific, lutherie becomes algorithmic, and performance becomes distributed across human and non-human actors [12].

1.3 Chelys Sonorum

These experiences shift attention from the mere production of sound toward the logics that organize and produce it. In this sense, the evolution of the electric guitar can be read as a transformation in how sound is modelled, negotiated, and made operative through instruments.

As Magnusson notes [13], the performative act is also an *ergodynamic* act, in which material, bodily, and sym-

bolic forces coexist and influence one another. Within this framework, *Chelys Sonorum* extends the principle of electromagnetic sustain toward a system in which feedback, retuning, and analysis interact to produce evolving sonic behaviour.

In Chelys Sonorum, quasi-autonomy refers to the instrument's ability to sustain feedback, retune its strings, and continue operating without continuous human intervention. The next sections outline the system design and its use in the installation I've Used to Play It, presented in Turin in autumn 2025.

2. SYSTEM DESIGN



Figure 1. *Chelys Sonorum* presented at Galleria Guido Costa Projects, Turin, 2025.

The physical body of the *Chelys* (Figure 1) integrates two main systems: a sustain system and a string-tension control system. [1] In this version, for ease of use and adaptability, a control software was developed in *Max* on *macOS*.

2.1 Sustain Hardware

Each string of the instrument integrates an independent sustain system inspired by the principle of the classic *E-Bow*. To realise this hexaphonic system, it was necessary to design and build custom pickups, each consisting of a 3D-printed bobbin, an *Alnico 5* magnetic core, and a winding of enamelled copper wire.

The design had to remain compatible with standard *humbucker*-type pickup housings, which imposed both dimensional and functional constraints. This meant accommodating approximately 6,500 turns of 42 AWG wire for the input pickups and about 450 turns of 32 AWG wire for the exciters, while also allowing tilt and height adjustment, leaving space for the magnetic core, and ensuring adequate thermal resistance.



Figure 2. Detail of the pickups and electromagnetic exciters of the *Chelys Sonorum*.

To increase the efficiency of magnetic coupling, additional *Neodymium* magnets with higher remanence were integrated at the base of the exciters, oriented to maintain consistency with the polarisation [2] of the main core. This configuration strengthens the magnetic field in the direction of the string, improving actuator sensitivity and feedback stability.

The support structure was modelled in *Rhinoceros* and printed in *ABS*, a material chosen for its higher thermal stability (up to $\sim$100°C) compared to common *PLA* (around $\sim$50°C). This requirement is essential since, during electromagnetic excitation, the pickup tends to heat up due to the supplied current [2]. In addition, the *wax potting* process constitutes a key finishing stage, as it prevents unwanted *microphonic feedback*, a critical issue in acoustic feedback systems [14, 15].

The windings of a pickup depend on its application. A traditional single-coil operates at high impedance (5-16 kΩ with 42 AWG or 43 AWG wire), providing a strong signal and a more coloured response. In other cases, such as sound design purposes, low-impedance pickups are more suitable, for instance around 500 Ω for a linear but weaker response [16], or coils of about 8 Ω for excitation purposes, designed to deliver current rather than capture signal.

To allow tilt and height adjustment, three screw holes were placed at the corners of the bobbin base, with three springs to keep it suspended. The output power of the exciters is insufficient to drive the string; they require additional current. To achieve this, six 5 W amplifiers based on the *LM386* [17] were employed, which can be eas-

[1] The instrument originates from the restoration of a damaged and disused *Yamaha RGX121Z* electric guitar.

[2] All exciters and pickups are aligned with the magnetic polarisation facing North, in order to ensure field coherence and maximise energy transfer.

ily and economically built by hand or purchased commercially. For the *Chelys*, six amplifiers are supplied with 9 V DC at 2 A, and operating them at one third of their range proved sufficient to obtain a clean and easily controllable feedback.

Due to the high number of input and output channels, *DB25* connectors were adopted as a more compact and cost-effective solution.

2.2 Tension Hardware

The main feature of the *Chelys Sonorum* is the dynamic control of string tension, which allows the tuning of the feedback to be altered in real time. For this purpose, six DC motors with gear reduction (3 V / 12 V) were employed, adapted to the tuning keys through 3D-printed components inserted into the rotating heads.

To drive the motors, only motor drivers and an *Arduino* system are required; in the *Chelys*, an *Arduino Mega 2560* and three *TB6612FNG* drivers are used. A single *TB6612* driver can control two motors in both directions, thanks to its integrated *H-bridge* and speed control.

Since the motors require a 12 V supply and at least 4-5 A of current, opto-isolators were added between the drivers and the *Arduino* for safety, preventing unwanted current returns that could damage the board or the computer's ports.

The support structure for the system is a semi-open plexiglass enclosure, custom-cut and fixed to the guitar's headstock.

2.3 Sustain Control Software

In order to control the sustain of the string, as in any acoustic feedback process, it is sufficient to design a gradual control of the amplitude of the signal taken from the input pickup and sent to the electromagnetic exciter in output, either digitally in software or in analog form through an amplifier.

To ensure greater stability and to avoid extreme peaks, it is recommended to place a limiter at the end of the chain; this prevents unwanted distortion and protects the exciter from overcurrent. The implementation of amplitude compensation systems such as compressors with slower attack times and gentler ratios, or systems based on amplitude descriptors such as *envelope followers* [18], also allows the feedback to be modelled in a more dynamically stable way.

Notably, the *E-Bow* is inherently mobile rather than fixed to the instrument body. When a pickup is mounted on a standard guitar, its position is necessarily static. Considering a string with fixed ends and vibrating length of approximately $L = 65\,\mathrm{cm}$, the available space for pickup placement (around 16–18 cm) corresponds roughly to the region between $\frac{1}{5}$ and $\frac{1}{4}$ of the string length. In practical terms, a neck pickup is positioned around $L/5$–$L/4$, while a bridge pickup lies closer to $L/13$–$L/16$ [19, 20]. In order to preserve the symbolic identity of a guitar, the present instrument retains a similar layout, making extreme positions such as the midpoint $L/2$ physically inaccessible to the exciter.

Given the fundamental relationship for the vibration modes of a stretched string [21]:

$$f_n = n \cdot \frac{v}{2L}, \qquad v = \sqrt{\frac{T}{\mu}}, \tag{1}$$

where f_n is the frequency of the nth mode (Hz), L the vibrating length (m), T the string tension (N), and μ the linear density (kg/m), the positions of the nodes are:

$$x_k = \frac{kL}{n}, \qquad k = 0, 1, 2, \ldots, n, \tag{2}$$

Where x_k is the position of the kth node (m).

When the electromagnetic exciter acts on position x_p, any mode whose node coincides with x_p receives no energy, since the string displacement is zero there, and is therefore suppressed. The resulting harmonic content thus depends directly on which modes present an antinode near the excitation point.

For example, placing the exciter at $x_p = L/2$ suppresses all even harmonics, whose nodes lie at that position, leaving the fundamental and odd partials as the perceptually dominant components. Conversely, at $x_p = L/3$, the modes with a node at one-third of the string length are suppressed, altering the spectral balance accordingly.

Since the exciter must operate at a fixed position corresponding to approximately one fifth of the string length—which, by its physical nature, enhances F_3 and F_5— it is necessary to place a filter at the end of the feedback chain to attenuate the higher-frequency components. A simple low-pass filter is sufficient to limit unwanted harmonic jumps.

Of course, this reasoning is purely physical-mathematical: in practice, many non-linear factors influence the performance of the string, such as stiffness, air resistance, friction at the nut and bridge, imperfect boundary conditions, and so on. Even the simple glissando resulting from changes in string tension alters the way the string vibrates: the lower the tension, the greater the flexibility of the string, and therefore its ability to bend and deform, increasing both the amplitude of transverse oscillations and the presence of higher harmonics.

To activate higher harmonics, it is still possible to intervene with a resonant filter (e.g., `lores~`, `reson~`) or with a passband wider than the fundamental. Therefore, precise control of the feedback requires an accurate description of the fundamental frequency, since an incorrect estimate may drive the system at the wrong frequency, causing unstable recursion and octave jumps.

2.4 Description of the Fundamental Frequency

In the case of an instrument excited through feedback, fundamental frequency analysis presents specific challenges. Pure feedback systems reject the logic of plucking, relying instead on the string's naturally slow attack. This fundamentally changes the playing field, since the system may stabilise on higher harmonics for extended periods, making fundamental-frequency estimation more difficult.

Conventional pitch-detection algorithms such as the *YIN* method [22] rely on signal periodicity in the time domain

and therefore perform less effectively when faced with strongly non-stationary harmonic structures. Unlike *YIN*, which measures the effective periodicity of the signal in the time domain, the *Harmonic Product Spectrum (HPS)* estimates the fundamental in the spectral domain [23]. The method is based on the coincidence of harmonic peaks, defined as:

$$Y(\omega) = \prod_{r=1}^{R} |X(\omega r)|, \tag{3}$$

where $X(\omega)$ represents the signal spectrum and R the number of harmonics considered. The fundamental frequency $\hat{f}_0$ then corresponds to the maximum of $Y(\omega)$:

$$\hat{f}_0 = \arg\max_{\omega_i} Y(\omega_i). \tag{4}$$

Where $X(\omega)$ represents the complex spectrum of the signal (with ω in $\mathrm{rad/s}$), and R the number of harmonics considered.

This approach makes possible to estimate the fundamental even when upper harmonics are more prominent than the first, a typical condition in electromagnetic feedback systems.

In *Max*, this method is implemented in the *fluid.pitch~* object [24]. To improve the stability of the estimation, the input signal is filtered with a 2 kHz low-pass filter, reducing the influence of higher-frequency components.

An analysis window of 2048 samples with a 50% overlap provides a good compromise, considering the inherently slow response of feedback systems. The latency introduced by this window is not critical in this context, as the instrument is not performed by a human in real time but rather left to evolve autonomously.

To mitigate tracking errors, estimates are further stabilised by sorting the most recent 250 measurements and selecting the most recurrent frequency. Finally, to prevent the analysis of silent or near-zero segments, the *fluid.ampgate~* object is used to suspend the analysis flow below a dynamic amplitude threshold.

2.5 Tension Control Software

To control the tension of the strings, a serial communication system was implemented between *Max* and *Arduino*. Commands are sent as ASCII strings consisting of five digits followed by a newline terminator (`\n`), following the structure `M D SSS`, where `M` identifies the motor (1–6), `D` the direction (0 = down, 1 = up), and `SSS` the speed (0–255, zero-padded to three digits). A value of 0 indicates stop, while 255 corresponds to the maximum permissible speed.

For example, the message `11148\n` means "motor 1, direction up, speed 148", whereas `50228\n` corresponds to "motor 5, direction down, speed 228". In *Max*, the values are combined using `sprintf` and sent to the serial port. On the microcontroller side, incoming characters are accumulated in a buffer until the newline terminator is detected. This approach, though simple, ensures robust frame delimitation, avoiding partial reads or synchronisation errors.

Once a complete frame has been received, the program parses it and activates the corresponding *PWM* and logic pins, sending the control signal to the *TB6612FNG* drivers. This configuration provides reliable, low-latency communication between the software environment and the motors, enabling continuous, time-varying control of string tension. To prevent over-tensioning or excessive detuning, the minimum and maximum limits for each string are stored in a *coll* object, which serves as a safety constraint.

3. EVALUATION AND EXPERIMENTAL OBSERVATIONS: I'VE USED TO PLAY IT

Between late September and early October 2025, the festival *To Listen To* [3], dedicated to experimental listening and electroacoustic sound practices, took place in Turin. Within this context, the installation *I've Used to Play It* [4] was presented, highlighting the expressive and emerging potential of the *Chelys Sonorum* system. The work was commissioned by the festival itself, alongside other installations distributed throughout the city of Turin.

3.1 Installation Context

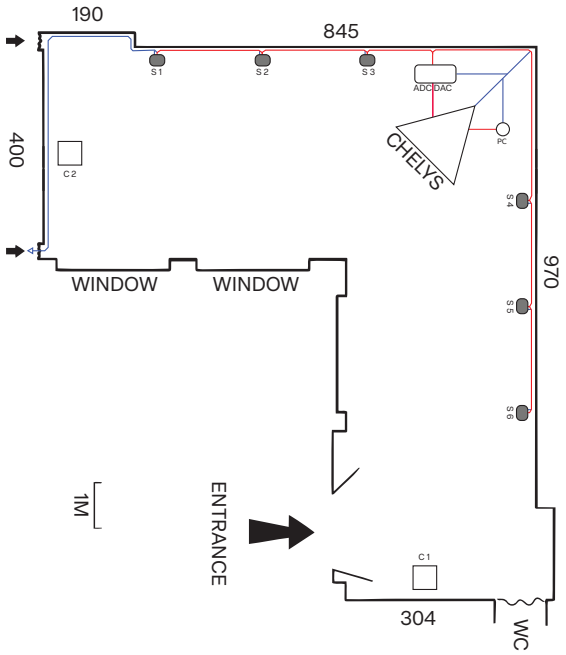

Figure 3. Floor plan of the Guido Costa Projects Gallery, showing the location of the *Chelys Sonorum* (triangle), the speakers (gray), and the cabling (red: audio, blue: electric).

The work was exhibited for two weeks in the space of the *Guido Costa Projects Gallery*, an irregularly L-shaped environment (Figure 3) that simultaneously hosted the installation *Eredi Boggiano* by Cristiano Berti. In this configuration, the *Chelys Sonorum* was required to adapt phys-

[3] The installation was presented at the *To Listen To* festival (Turin, 2025). Further information is available on the Official Website Page. A promotional video is available on YouTube.

[4] The title *I've Used to Play It* is deliberately ungrammatical, combining incompatible verb tenses to evoke a sense of temporal displacement, as if the instrument were recalling a past action without certainty about when, or whether, it had actually occurred.

ically and conceptually the work to the existing installation, thereby creating a visual and acoustic dialogue with the family tree presented in Berti's work. The installation also had to address practical constraints for continuous and reliable operation: a simplified power-on system (a single activation switch), electrical safety, and the ability to automatically suspend activity during prolonged absence of visitors.

3.2 Technical Setup

The technical system included:

- an *Antelope Orion 32* audio interface with six inputs and twelve outputs in use;
- six *Genelec 8040* speakers arranged along the perimeter of the space;
- six instrument preamps for the *Chelys* pickups;
- a *Mac Pro* running the *Max* patch, executed automatically at startup via a system script.

The control patch at startup processed:

1. loading of the audio interface and *Arduino* firmware;
2. initialization of the databases;
3. synchronization of the sampling frequency;
4. an ascending tension on the tuning pegs to compensate for the previous session;
5. activation of the installation.

The guitar was placed in the inner corner of the room, on a stand, vertically illuminated by a projector with light shaped onto it. The cables and connections, deliberately exposed, created a visual texture that evoked the imagery of a disorganized rehearsal session, as if the instrument had been left abandoned after its last use.

3.3 System Behavior

Over nearly two weeks of operation, spanning approximately four hours daily, the *Chelys Sonorum* maintained stable performance: the pickups never reached critical temperatures, and the strings did not detune to the point of unwinding from their mounts. Two adapters connecting the tuning keys to the motors were replaced, likely due to their age. Only one string, a .009 high E, broke during setup, with no further malfunctions.

The music generation logic relied on an autonomous memory system: a database created with *dada.base* [25] contained approximately sixty *riffs* drawn from pop, rock, jazz, and metal tracks (see Table 1).

Each fragment is analysed with a *chroma* descriptor using *earx.essentia∼* [5] . Prior to track analysis, the *riff* was extracted as follows:

1. Manual editing in a *DAW* to isolate the riff (approximately 4-20 seconds);

#	Title / Artist
01	Les Paul & Mary Ford – *Vaya Con Dios*
02	Bee Gees – *Stayin' Alive*
03	King Crimson – *Starless*
04	Radiohead – *No Surprises*
05	Ramones – *Blitzkrieg Bop*
06	Pat Metheny – *Bright Size Life*
07	Jethro Tull – *Aqualung*
08	Slint – *Breadcrumb Trail*
09	Area – *Luglio, Agosto, Settembre (Nero)*
	...
58	Death – *Symbolic*

Table 1. Sample of tracks included in the chroma analysis database.

2. extraction of the "other" component using a *demucs* model integrated into the open-source program *Ultimate Vocal Remover* [6] .

Each node was subsequently processed as follows:

1. Loading of the folder containing the *riffs*;
2. Volume normalization;
3. Analysis of long-term loudness to derive a value for adjusting the activation threshold of an onset detector;
4. Onset detection;
5. Analysis of Harmonic Pitch Class Profiles (*HPCP*) from onset points;
6. Storage of results in a *dada.base* database.

Once the analyses were extracted, distances were symmetrically calculated between the feature vectors in the database, translating the similarity between two chromatic profiles into a normalized numerical value. Each pair of nodes was compared such that the resulting measure depended not on the amplitude of the data but solely on its shape, yielding a stable and comparable tonal proximity index. In practice, the system assessed how closely two spectral distributions "pointed in the same direction," constructing a coherent map of internal relationships within the database (see Figure 4). The strongest magnitudes then generated harmonic distances, subsequently reused to determine pitch and string successions. The task of distributing pitches to strings was handled by an algorithm that populated a table prioritizing certain strings. These priorities were calculated based on: recent activity, silence duration, sound intensity over time (*LUFS*), which strings were currently playing, which had recently stopped, and the degree of tuning deviation to be addressed. The slow, deliberate movement of the tuning pegs produced continuous micro-variations in tension, and thus intonation, creating a sense of instability and "frozen" time.

[5] *earx.essentia∼* implements select algorithms from *Essentia*, an open-source *C++* library for audio analysis and music information retrieval - More infos at: https://essentia.upf.edu/

[6] Software used for audio source separation. Further details at: https://ultimatevocalremover.com/..

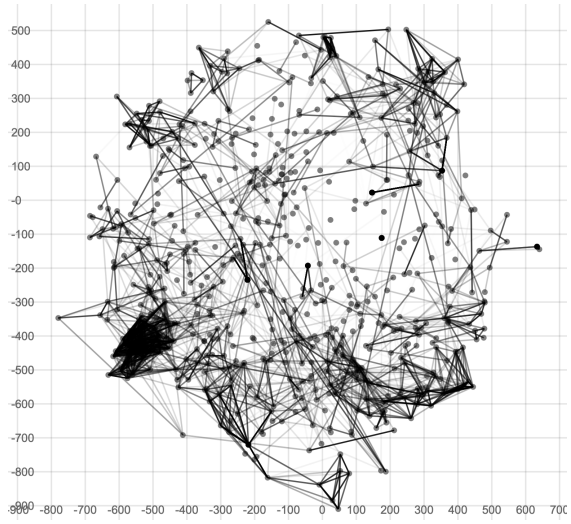

Figure 4. Distribution of nodes in the database based on chroma analyses of the tracks.

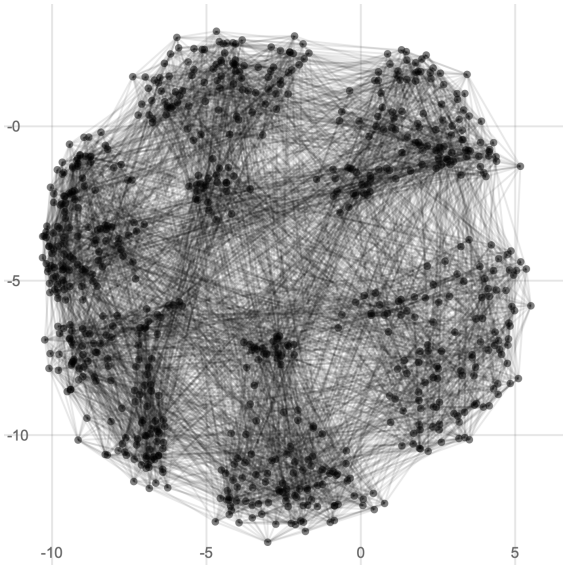

Figure 5. Distribution of nodes in the database related to sound spatialization.

In practice, the riffs functioned as behavioural triggers that displaced sonic stasis. By drawing on idiomatic guitar repertoires, the system activated culturally loaded fragments that persisted as formal traces even when they were no longer clearly recognizable as source material.

3.4 Compositional and Spatial Analysis

The resulting musical discourse does not emulate a human guitar performance but evokes the "ghost" of a sonic memory, a performative residue emerging from material persistence and machine autonomy [26], resonating with Emmerson's notion of "living electronic music" as a reanimation of sonic material. The strings produce "notes" without attack, generating spectral harmonies in continuous drift. The combination of amplitude analysis (in *LUFS*) and frequency analysis enables progressive opening or closing of a resonant low-pass filter (lores∼), alternately bringing out the fundamental or upper harmonics. The spatialization system, also built on *dada.base* (see Figure 5), dynamically distributes the sounds from the six string modules across the six output channels, following slow, non-repetitive trajectories.

An additional layer of spatialization is provided by the instrument's own acoustics: the semi-acoustic vibration of the strings and the hum of the motors generate an autonomous, almost entomological sound component that interacts with the amplified output, enhancing its immersive perception.

4. CONCLUSIONS AND FUTURE DEVELOPMENTS

The installation *I've Used to Play It* demonstrated that *Chelys Sonorum* can operate as a robust quasi-autonomous electroacoustic system over extended periods with limited technical intervention. In unattended installation conditions, the instrument sustained a variable yet coherent sonic behaviour through the interaction of electromagnetic feedback, motorized retuning, and rule-based control.

At the same time, the case study exposed a clear analytical limitation. Chroma-based analysis proved less effective than expected, largely because continuous feedback conditions made the estimation of the fundamental frequency unstable when the system locked onto upper harmonic components. As a consequence, source materials often remained only partially recognizable, if not entirely unidentifiable. This suggests the need for a different identification strategy, for example by looping the materials and letting the system reiterate them until the riff becomes more clear.

Future work should therefore focus on strengthening the relation between string state, pitch estimation, and control. The most relevant directions include more direct sensing of the tension–intonation relationship, improved hardware management of the balance between fundamental and upper harmonics, and the integration of embedded computation to reduce dependence on an external computer.

More broadly, Chelys Sonorum demonstrates that hybrid guitar systems generate forms of behaviour, instability, and memory specific to their material and algorithmic design.

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