MIDI ADAPTIVE TUNING STRATEGIES BY MEANS OF AI-BASED STRUCK-STRING INTERACTION IN UBIMUS

RUI SU[1]· JOSEPH TIMONEY[2]· DAMIÁN KELLER[3]

RUI.SU.2022@MUMAIL.IE - JTIMONEY@MU.IE - DKELLER@CCRMA.STANFORD.EDU

ABSTRACT

The struck-string interaction framework provides fresh opportunities for exploration of adaptive approaches to tuning. A particularly interesting intersection of ubimus developments is the convergence of tuning with timbre-based interaction. Our analysis highlights that whereas conventional tuning techniques offer a strong theoretical and practical basis, the addition of adaptive technologies has the potential to increase flexibility. Therefore, we engage with two areas of focus within struck-string interaction: the ubimus networked-based infrastructure and the expanded notions of inharmonicity.

KEYWORDS

Struck-string interaction; tuning; adaptive techniques; inharmonicity.

1 INTRODUCTION

This paper reviews the development of tuning systems while analysing how current technology may be able to address long-standing issues of just-intonation (JI) implementations, with an emphasis on piano sounds.

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1. Maynooth University, Ireland.
2. NAP, Federal University of Acre, Brazil. Ubiquitous Music Group.

We examine the state-of-the-art in piano-timbre technologies, from physical modelling to sampling, to probe the potential and constraints of fixed-pitch tuning architectures. We discuss how Just Intonation, long thought to be impracticable, may be enabled within ubiquitous music environments by fusing historical philosophy with adaptive computational techniques. After discussing recent developments in AI-driven adaptive tuning, we speculate on a web-based JI plugin design that uses chord analysis and real-time pitch recognition.

The widespread usage of 12-tone Equal Temperament (12-TET) in the late Renaissance and Baroque was a result of centuries of tuning system innovations and compromises. In contrast to previous systems and fostering the adoption of tonality, 12-TET ensured uniform intervals across all keys by dividing the octave into twelve equal logarithmic steps. This homogeneity impacted pitch-based compositional practices enabling easier key modulations when compared to Pythagorean and Meantone tuning systems (Stange et al., 2018). 12-TET deviates slightly from natural frequency ratios. While guaranteeing consistent modulations, the 12-TET approach features slight dissonances dispersed across the scale, sacrificing the clean-sounding, beat-free intervals of Just Intonation. In contrast, JI produces harmonic series-aligned intervals that have a warm, resonant quality but it rapidly becomes unwieldy in multi-key settings. This diversity of approaches to tuning suggests a potential conflict between practicality and purity, exemplified by the adoption of equal temperament as an alternative to just intonation, that has not been resolved[3].

[Indent]Many current musical practices use tunings based on natural intervals, such as the systems based on Chinese pentatonic scales which prioritise simplicity and resonance, and the Indian Shrutis, which divide the octave into 22 microtonal steps. Adaptive tuning algorithms may foster new paths for developing legacy tuning systems that so far have been constrained by fixed-pitch instruments.

[Indent]The remaining sections examine how tuning is being reconsidered through the application of artificial-intelligence and digital signal processing tools, in an effort to find adaptive solutions. The first section explains prior work on tuning systems and discusses their advantages and limitations, including alternative tunings, dynamic adaptive intonation, and just intonation algorithms. The second section explores the technical requirements for the development of struck-string interaction prototypes, highlighting network-based infrastructure and expanded inharmonicity as areas of focus. We then present musical examples and provide pointers to future design efforts in struck-string interaction.

JUST INTONATION

Just Intonation is a tuning method based on straightforward rational frequency ratios (see also Hermode Tuning below). This approach may be summarised as

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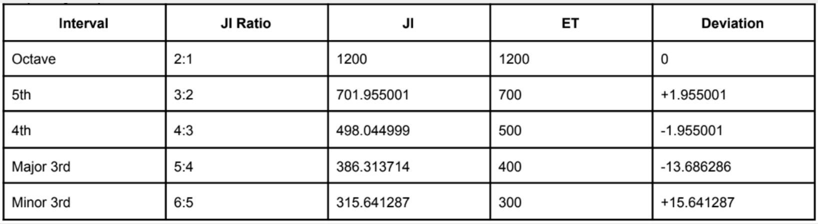
3. Our approach to tackling multiple tuning systems within a consistent framework stems from a ubimus-design perspective of expanding the aesthetic pliability of music-making. Similarly to meter-based temporalities, current tuning techniques restrict the range of sonic organisations to a subset of preset options.

continually solving a system of linear equations, as opposed to making a series of if-then decisions. The set of equations can be thought of as a mechanical network of springs or resistors representing the interval sizes. Each spring will, whenever feasible, tend toward a state where its length matches the size of a pure interval. If the spring network is very intricate and it is not feasible for every spring to be in its ground state, the system may approach a non-trivial state under tension (e.g., a tempered harmonic compromise). This may be compared to how musicians discover in-tune intervals. A benefit of this approach is that it finds a balanced set of all the targeted intervals, not just nearby tones (Stange et al., 2018).

TABLE 1. COMPARATIVE ANALYSIS OF JUST INTONATION (JI) AND EQUAL TEMPERAMENT (ET) INTERVAL VALUES. THIS TABLE DISPLAYS VALUES FOR PREVALENT MUSICAL INTERVALS ACCORDING TO JUST INTONATION RATIOS AND EQUAL TEMPERAMENT, INCLUDING THE VARIANCES IN CENTS. IT ILLUSTRATES THE DISTINCTIONS BETWEEN THE TWO TUNING SYSTEMS, EMPHASISING THE SMALL FREQUENCY DISPARITIES INHERENT IN EACH METHOD



Interval	JI Ratio	JI	ET	Deviation
Octave	2:1	1200	1200	0
5th	3:2	701.955001	700	+1.955001
4th	4:3	498.044999	500	-1.955001
Major 3rd	5:4	386.313714	400	-13.686286
Minor 3rd	6:5	315.641287	300	+15.641287

In contrast to other tuning techniques, just intonation uses vertical and horizontal harmony to tune the pitch content. Adaptive tuning methods face two significant tuning aspects, as pointed out by Stange et al. (2018). On the one hand, every new chord must be intoned ‘vertically,’ meaning the relative pitches are performed simultaneously. However, the harmonic progression requires the following chords to be adjusted in relation to one another according to ‘horizontal’ (or sequential) criteria[4]. In just intonation, the twelve pitch classes are adjusted so that, with respect to a certain reference frequency f∗, all frequency ratios can be expressed as simple rational values. The steady migration of the overall pitch is one of the main drawbacks of dynamic tuning methods that rely on sequential methods.

Stange, Wick, and Hinrichsen (2018) describe an implementation of JI that features built-in microtonal sound generators and real-time MIDI instrument modifications. Its support of dynamic polyphony and pitch-bend commands enables experiments with adaptive tuning and comparisons of the outcomes of JI with ET and other static tunings.

Another method, based on the psychoacoustic concept of dissonance, was proposed by Sethares (2002). In order to establish a cost function for a gradient-based optimisation process, the system continuously responds to the changes in JI ratios. By lowering the expense parameter, the pitches are automatically adjusted to reduce dissonance. An example of how a dynamic tuning model can lessen the dissonance was presented in Kirsch and coauthors’ work (Kirsch, 2021). Their algorithm minimises estimated roughness between simultaneous pitches or chords by optimising frequencies. The algorithm was then adjusted to optimise the dissonance reduction after the results were compared to conventional tuning techniques. The overall

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[4] Combinations of tones are typically interpreted as either in tune or out of tune when performed simultaneously. But their intonation is also relevant consecutively. Smooth harmonic transitions tend to focus on the pitches of succeeding chords to account for intonational memory. Consequently, an intonational discontinuity between chords may result from an abrupt change in the chordal root if the chords are unrelated.

computed dissonance reduction averaged up to 12%.

ALTERNATIVE TUNINGS

Kite Giedraitis' Alt-tuner was created as a plug-in for digital audio workstations (DAWs) to offer a versatile platform and dynamic pitch adjustment for recordings and live performances based on the MIDI protocol (Giedraitis et al., 2019). Particularly in JI, Alt-tuner's ability to adjust tunings on the fly provides support for group performances in multi-keyboard setups. Alt-tuner offers meantone, various equal temperaments, and microtonal scale tunings in addition to just intonation tuning. Additionally, it features a user-defined tuning system that lets users create their own scales.

Nevertheless, Alt-tuner has some drawbacks due to a complicated procedure that necessitates knowledge of tuning systems, microtonal ideas, and just intonation ratios. Thus, its custom settings can be difficult for novices. Given that not all DAWs natively support microtonal tuning, its reliance on a DAW is also a caveat.

HERMODE TUNING

Hermode Tuning (HMT) is a method for dynamically tuning virtual instruments (Mohrlok, 2003). The implementation is predicated on the notion of examining harmonic structures and adjusting pitches to achieve a consistent intonation. To maintain compatibility with well-known tools, HMT also supports re-tuning based on equal temperament.

Over time, a number of tuning techniques have been developed; Hermode Tuning is among the well-known adaptive tuning systems, with applications ranging from plug-ins for software programs like Cubase to implementations in church organs. Rather than figuring out the chordal root, the algorithm adjusts intervals between the vertically adjacent tones of a particular chord to fit specific ratios. To minimise deviations from the standard equal-temperament, the pitch of the fundamental is simultaneously modified. As a result, this reduces the frequency shifts between subsequent chords (Stange et al., 2018). Figure 1 shows how HMT tunes A major chords and their resulting differential tones.

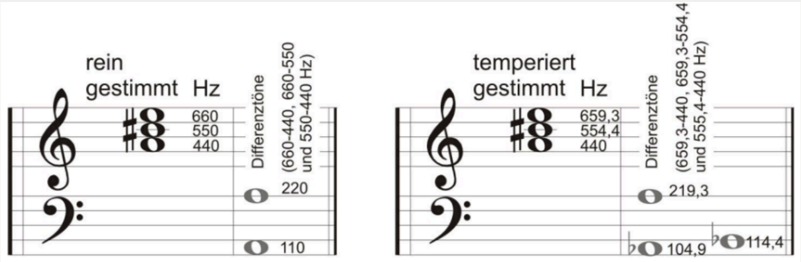


FIGURE 1. 12-TET A MAJOR CHORD VS. HMT-TUNED A MAJOR CHORD (MOHRLOK, 2003)

Hermode tuning allows selecting a preferred tuning style. Distinct tuning modes prioritise just intonation. All HMT modes, for instance, restrict the effective line of equal temperament's variation from a baseline of +/-20 cents. This indicates that no frequency can vary from the level of equal temperament by more than +/-30 cents. The natural seventh in the HMT mode Jazz/Pop is the only exception, with a largest deviation set to -47 cents.

In contrast to previous adaptive tuning techniques, the concept of harmonic centre guarantees that tuning stays constant across key changes, thus avoiding sudden shifts.

The current harmonic centre is determined by analysing the last 10 chords and saving the computed tuning values in memory. Only the tuning values of the final ten chord structures remain, substituting the first, second, etc. from the ongoing analysis as a new harmonic centre emerges.

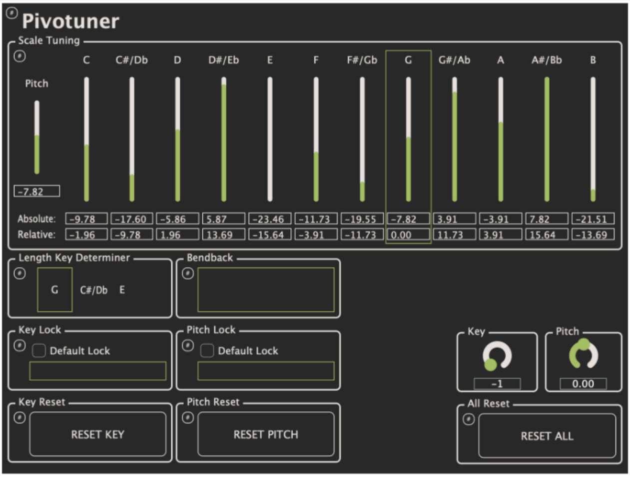
HMT applies just intonation modifications through smooth harmonic transitions but it may present certain drawbacks: due to its heavy reliance on equal temperament and just intonation, HMT might not be able to handle alternative scales; the majority of DAWs do not support it; furthermore, in highly chromatic music where harmonies change quickly, it may not have enough information to establish a definite harmonic centre.

PIVOTUNER

The VST3/AU MIDI plugin Pivotuner automatically adjusts pitch data to provide support for adaptive pure intonation (Volkov, 2023). Finding a reference key is a first step: Pivotuner employs a Key Determiner method to identify a reference note to adjust the pitches of a MIDI data stream. After identifying a key, Pivotuner determines how to tune the subsequent notes. Provided that non-equal temperament intervals are specified, Anytime the Key Determiner reports a new key, a microtonal modulation takes place, (Volkov, 2023). The Pivotuner plugin interface is featured in figure 2.

Then, using an adjustable-tuning algorithm, Pivotuner adjusts the active pitches in relation to the given key. In addition to choosing the algorithm for key and tuning selection. It also provides ways to regulate the settings when a new key is selected, to control microtonal modulation, and to tune each interval and chord individually.

Pivotuner does have some limitations, though. For intervals from minor 2nd to major 7th, Pivotuner allows the use of any tuning; however, up to this point, only ratio-based pure tunings have been employed. Additionally, Pivotuner has not been utilised in live settings with voice or acoustic instruments. Although performing microtonal music with voice or on acoustic instruments is challenging, the proposed technique might be able to supply microtonal reference pitches to make this approach deployable in performances (Volkov, 2023).



Pitch -7.82

	C	C#/Db	D	D#/Eb	E	F	F#/Gb	G	G#/Ab	A	A#/Bb	B
Absolute:	-9.78	-17.60	-5.86	5.87	-23.46	-11.73	-19.55	-7.82	3.91	-3.91	7.82	-21.51
Relative:	-1.96	-9.78	1.96	13.69	-15.64	-3.91	-11.73	0.00	11.73	3.91	15.64	-13.69

Key -1

Pitch 0.00

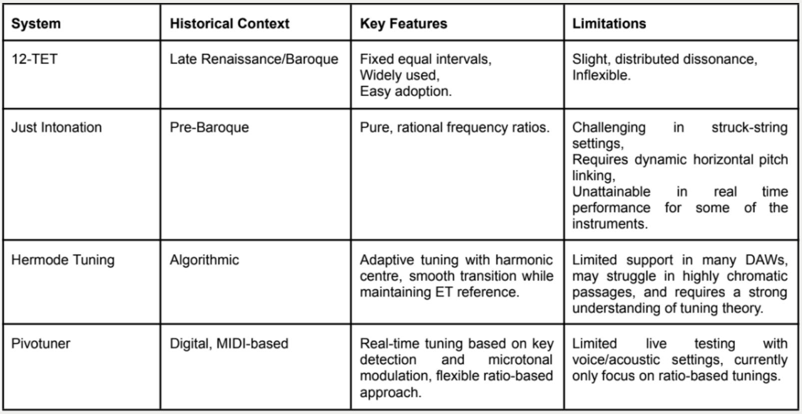
FIGURE 2. PIVOTUNER USER INTERFACE (VOLKOV, 2023)

MULTI-PITCH ESTIMATION

The research team from Deep Autotuner created a machine learning algorithm that uses instrumental accompaniment recordings as references to predict pitch correction for a monophonic vocal track (Wager et al., 2020). Additionally, their findings on a CNN with a GRU layer show that the amount of pitch correction may be determined with the help of spectral information extracted from the vocal and accompaniment tracks.

Deep learning techniques based on convolutional architectures and HCQT input constitute an efficient and reliable approach to general-purpose MPE (Multi-Pitch Estimation). According to Weis and Peeters's (2022) comparison of various architectures based on convolutional neural networks, the U-net structure, and self-attention components. This approach to deep learning might handle pitch information extraction which in turn may support Just Intonation tuning implementations.

TABLE 2. COMPARATIVE ANALYSIS OF TUNING SYSTEMS. THIS TABLE COMPARES HISTORICAL CONTEXT, PRIMARY FEATURES, AND CONSTRAINTS OF FOUR TUNING SYSTEMS: 12-TONE EQUAL TEMPERAMENT (12-TET), JUST INTONATION (JI), HERMODE TUNING (HMT), AND PIVOTUNER. IT OFFERS A SUCCINCT COMPARISON TO FACILITATE COMPREHENSION OF THEIR HISTORICAL DEVELOPMENT AND TECHNICAL INTRICACIES



System	Historical Context	Key Features	Limitations
12-TET	Late Renaissance/Baroque	Fixed equal intervals, Widely used, Easy adoption.	Slight, distributed dissonance, Inflexible.
Just Intonation	Pre-Baroque	Pure, rational frequency ratios.	Challenging in struck-string settings, Requires dynamic horizontal pitch linking, Unattainable in real time performance for some of the instruments.
Hermode Tuning	Algorithmic	Adaptive tuning with harmonic centre, smooth transition while maintaining ET reference.	Limited support in many DAWs, may struggle in highly chromatic passages, and requires a strong understanding of tuning theory.
Pivotuner	Digital, MIDI-based	Real-time tuning based on key detection and microtonal modulation, flexible ratio-based approach.	Limited live testing with voice/acoustic settings, currently only focus on ratio-based tunings.

This section reviewed approaches to dynamic tuning, highlighting caveats and opportunities for deployment in the context of struck-string interaction. Tuning approaches have traditionally focused on the organisation of scales and pitch-oriented strategies strongly based on tonality. More flexible techniques may be fostered through the application of adaptive, context-sensitive techniques and a focus on timbre-based interaction. We will develop these ideas in the next sections. Having covered the recent work on tuning systems, we now turn to struck-string interaction developments. Our analysis of requirements highlights two areas of focus: network-based requirements and applications of inharmonicity.

APPLICATIONS OF ADAPTIVE TUNING STRATEGIES IN STRUCK-STRING INTERACTION: EXPANDED PIANO INHARMONICITY

When an object is struck or plucked, its fundamental frequency is the natural frequency at which it vibrates, creating the lowest and most prominent pitch. The harmonic series is made up of integer multiples of a vibrating object's lowest frequency. However, piano strings feature in-harmonic partials—resonant frequencies that differ from these harmonics. This discrepancy arises because ideal strings devoid of stiffness are assumed by the idealised harmonic series, which is never the case in practice. Inharmonicity is the term used to describe the extent of this deviation caused by the stiffness of strings. Tuning relies heavily on inharmonicity (Roy, 2024).

Fletcher arrived at the equation of motion of a string fixed at either end, taking into account the tension and elastic stiffness that produce a restoring force, as well as the energy conservation principles in the bending and stretching of the string (Rasch & Heetvelt, 1985; Roy, 2024). In equation 1, the frequency, fn, represents the nth mode of a string, where the frequencies of any two modes may be precisely measured to yield two constants, *F* and *B*. *B*, which has units of $m^{-2}s^{2}$, is the inharmonicity coefficient. The structural characteristics of piano strings, such as material stiffness and diameter-to-length ratios, cause deviations that are measured by the inharmonicity coefficient *B*.

$$f_n = nF\sqrt{(1 + Bn^2)}, \qquad \text{(EQUATION 1)}$$

Commonly seen in lower-register piano strings, the magnitude of B increases with shorter lengths and thicker strings (Dalmont, 2021). This effect is particularly important for lower bass strings, especially for smaller pianos where normally they would feature very thick strings relative to their length. Generally speaking, larger pianos tend to have longer strings so generally exhibit lower inharmonicity, particularly in the bass. Typically, a piano's lower tones have "wound" strings, the middle and upper tones "plain" strings. On the average, the inharmonicity of the wound strings is smaller than that of the plain strings – inharmonicity is not consistent over the keyboard; in the wound portion, it generally rises as one descends the keyboard , while in the plain wire section, inharmonicity tends to be low around the middle registers (like the octave below C4) and increases towards the higher notes (Rasch & Heetvelt, 1985). The

Railsback curve, which shows variations from equal temperament tuning across the keyboard, has been widely modelled and connected with stretched tuning, a typical aspect of piano tuning (Jaatinen and Pätynen, 2022; Rasch and Heetvelt, 1985).

Piano tones' inharmonicity results in a tuning curve quite different from its idealised harmonic counterpart and resembles the Railsback curve. For aural piano-tuning, beats are essential. In other words, the inharmonicity of the strings has a major impact on the tuning stretch. According to Jaatinen and Pätynen (2022), most of the inharmonics are heard as higher in the low and middle registers (up to C#7). Uncertainty tones and no discernible patterns are featured in the highest register (above C#7). Subjective octave experiment's findings are in line with those of professional musicians, despite the fact that some of the tuners have no prior experience performing music. Inharmonicity may no longer play a significant role in correcting pitch recognition because the majority of harmonics in the highest register reach the human pitch detection limits. Thus, the subjective octave-based approach replaces the beat-based approach at the highest register (Jaatinen and Pätynen, 2022).

Inharmonicity has been the subject of several investigations involving materials. Optimising string winding and shape to balance stiffness and harmonicity is one example of a construction method. Recent developments concentrate on analytical and experimental material techniques, like adding mass close to the string ends or using string densities that vary sinusoidally (Dalmont, 2021). Acoustic pianos could be expanded through experimental research on temperature-dependent self-tuning systems, aiming to avoid manual tuning (Roy, 2024).

Having discussed inharmonicity as a target application in struck-string interaction, we now turn to methods to enable flexible tuning techniques. We build on a ubimus tradition of recycling technological resources for innovation. Thus reducing the ecological footprint while expanding the integration of ubimus infrastructure.

UBIMUS NETWORKED-BASED SSI DEPLOYMENTS: WEB MIDI AND MIDI 2.0

MIDI (Musical Instrument Digital Interface), a well-known technical standard, is still widely used in the fields of electronic music creation and musical information retrieval even after four decades of use. A recent development is MIDI 2.0, made available in the early 2020s. MIDI 2.0 is an update to the MIDI specification that aims to address part of the shortcomings of the original MIDI 1.0 protocol. In addition to providing space in the specification for upcoming advances, MIDI 2.0 seeks to increase the range of tools while maintaining backward compatibility with the extant MIDI 1.0 infrastructure.

MIDI 2.0 has features relevant to adaptive tuning and struck-string interaction. By including techniques for two-way communication between MIDI devices using MIDI Capability Inquiry (MIDI-CI) messages to send and receive device information, it overcomes some of the shortcomings of the original MIDI standard. New features include an enlarged data format for higher resolution with extensibility targeting future definitions of messages, as well as auto-configuration by bidirectional connections that allows devices to discover details about other connected devices.

Importantly, it standardizes per-note controllers, letting parameters like pitch bend, expression, or articulation data affect individual events, instead of the whole MIDI channel. This refinement presents interesting possibilities for complex adaptive tuning techniques, including dynamic Just Intonation. Figure 4 shows a comparison between channel-based control of MIDI 1.0 and per-note capability of MIDI 2.0. Although hardware and software adoption is still in progress, some devices have already implemented MIDI 2.0.

Developed by W3C Audio Working Group, the Web MIDI application programming interface (API) aims to bring MIDI to the Web by enabling communication and interaction between a browser application and MIDI devices. One of the goals is to make MIDI devices support a standard feature of OS systems and web browsers on various hardware platforms. The aim is to allow web applications to communicate directly with MIDI-enabled devices, increasing accessibility for online music production and live performances (Baratè & Ludovico, 2022). Web applications may list, choose, and communicate with MIDI input/output devices thanks to the JavaScript interfaces that the Web MIDI API exposes. Because of this integration, software installations are no longer necessary, fostering the expansion of web-based DAWs, MIDI controllers, and interactive music applications. Web MIDI API has already achieved some level of low latency and real-time communication. However, it also faces difficulties, even though popular browsers like Google Chrome and Edge support it, platform popularity is still developing. Widespread adoption has been hampered by security concerns, especially those related to device access and potentially harmful interactions (Baratè &

Ludovico, 2022). Furthermore, support for accurate timing is limited (Keller and Lazzarini, 2024).

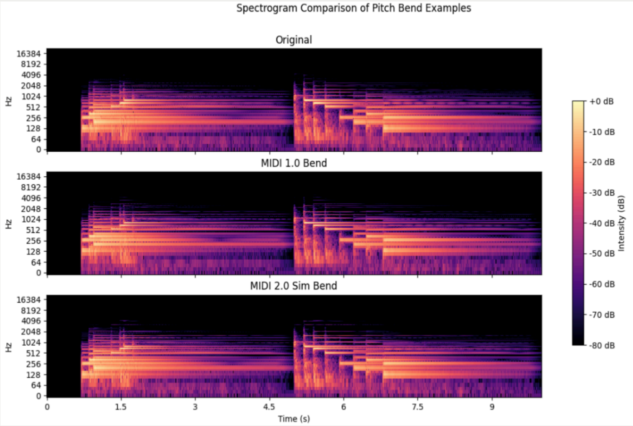


FIGURE 3. SPECTROGRAM COMPARISON ILLUSTRATING MIDI 1.0 VS. SIMULATED MIDI 2.0 PITCH CONTROL ON A C MAJOR CHORD. THE SPECTROGRAM SHOWS THE TIME VS. FREQUENCY. WITH THE TOP SCALE WE CAN SEE IT HAS THE MOST STABLE FREQUENCIES. THE MIDDLE SCALE REPRESENTS MIDI 1.0 PITCH BEND, WITH HARMONICS OF ALL NOTES CURVE SIMULTANEOUSLY (ESPECIALLY FROM 1.5S - 3S). AT THE BOTTOM SCALE, MIDI 2.0 PER NOTE SIMULATION, HARMONICS OF STABLE NOTES (C4, G4, C5) REMAIN STRAIGHT, WHILE ONLY THE HARMONICS OF THE TARGET (E4 ~ 392 HZ) CURVE, DEMONSTRATING INDEPENDENT PITCH CONTROL CRUCIAL FOR PRECISE ADAPTIVE TUNING. SAMPLE AUDIOS IN APPENDIX.

Tools like Midiano[5] feature the possibility of running MIDI apps straight in the browser using the Web MIDI API. Users of this web software can load standard MIDI files, see the events (usually in a 'piano roll' or falling-note style), link a physical MIDI unit for interactive playback and feedback, and set the playback speed.

OPEN ISSUES AND FUTURE DEVELOPMENTS

Our study of the state-of-the-art in adaptive tuning shows

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[5] https://midiano.com/

that some progress has been made in the last decades but there are still problems with accessibility, polyphonic control, and aesthetic pliability. This suggests a direction for future research: developing a comprehensive, browser-based framework that combines the emerging techniques while targeting an aesthetically flexible design. Future struck-string interaction systems should not only address long-standing issues related to Just Intonation, they may also foster new possibilities in timbre manipulation, for instance, by featuring dynamic control of piano string inharmonicity. Therefore, two areas of focus for the development of struck-string interaction are proposed: integrated development of ubimus networked-based infrastructure and the expanded notions of inharmonicity enabled by adaptive tuning.

Inharmonicity is inherent to piano strings yielding acoustic features that distinguish each instrument. Theoretical knowledge, practical engineering, and psychoacoustic considerations are necessary to balance its effects. Our understanding and use of this phenomenon will grow as research progresses thanks to a stronger connection between the physics of sound and the craft of music.

Machine-learning pitch detection and adaptive tunings may offer the subtle nuance required to replicate the retuning practices done by musicians and musicologists in their daily studies. By analysing live musical contexts and implementing per-event control capabilities based on the latest updated protocol MIDI 2.0, ubimus systems may be capable of aligning the current tuning with rapid changes of pitch-based systems. Taken together, the approaches discussed in this paper show how tuning systems and cutting-edge technologies open up new possibilities and increase the viability of using Just Intonation in both legacy and prospective ubimus frameworks.

Nevertheless, special attention needs to be given to the emergent caveats of the adoption of AI-based tools. Despite the fact that ethical and political concerns surrounding AI tools have gained more attention in recent decades, there has been a dearth of research on the effects of AI techniques on music communities. The OECD AI standards and nine well-known ethical statements were examined by Oğul (2024), pointing to a tentative convergence towards transparency, human-centered values, fairness, and privacy standards. This initiative may offer a useful framework for the development and application of responsible AI in emergent, community-based music practices.

Stricter ethical standards should be enforced. For instance, some generative systems adopted by the music industry do not take into account the environmental impact of their use, from energy consumption to hardware lifecycle. We hope that the continuous efforts of the ubimus community may eventually open the door to AI applications that work in concert with humans to create dynamic and morally sound musical practices.

Our ongoing work targeting dynamic tuning mechanisms, featuring browser-based toolkits, may tackle inharmonicity issues in piano sounds by applying predefined tuning ratios (Su et al., 2024). This approach bridges theoretical tuning models with web deployment. Building on that foundation, we are currently updating the code base to support MIDI 2.0 and AI-based adaptive techniques. Challenges such as latency, computational load, and ensuring the accuracy of pitch detection remain active areas for research. Our next steps focus on refining these issues,incorporating feedback from performance trials, and exploring the integration of emerging technologies like edge computing and cloud services.

The next important step is to validate such a system thoroughly. Testing its strengths and weaknesses involves using musical excerpts for comparative analysis with the latest state-of-the-art systems. One way to check for vertical tuning purity is to process MIDI recordings of harmonically stable pieces, like a J.S. Bach chorale. On the other hand, pieces from highly chromatic late-Romantic works or jazz excerpts that feature harmonic complexity would test the reactive algorithm's preciseness and malleability during key changes. Then, we may compare the performance of the system to tools like Pivotuner and Hermode Tuning to achieve a quantitative and qualitative benchmark.

Finally, another way to progress would be to go beyond pitch sequences and look into how adaptive tuning can be used on timbre itself. The suggested framework could be used in additive synthesis as well. Instead of just changing the fundamental pitch, the system could be designed in a way to change the inharmonicity of the partials, and to change the synthesised piano tones to match the detected harmonic context. This combination of adaptive tuning and real-time timbral synthesis is an area for artists and engineers to explore in future struck-string interaction initiatives. In conclusion, grounded on solid musical tuning theories and cutting-edge adaptive techniques, struck-string interaction tuning may open new avenues for artistic exploration.

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APPENDIX

Audio Example 1: Reference C Major chord, no pitch bend. https://drive.google.com/file/d/1wOnWHfat7QgVhZVBnDKxCzcV2vOtHnyX/view?usp=sharing

Audio Example 2: C Major with MIDI 1.0 channel pitch bend (all notes bend simultaneously). https://drive.google.com/file/d/18Po_wOJ-HIOmStQNeYpy6bY6FcXch9qZ/view?usp=sharing

Audio Example 3: C Major simulating MIDI 2.0 per-note pitch bend (E4 bends independently). https://drive.google.com/file/d/1Rc3vF_pA9pC6BNbm3yT5F6XHNZ-ahRi4/view?usp=sharing