LIMITS OF GEOMETRIC PLUCK CALIBRATION FOR REPEATABLE ROBOTIC EXCITATION OF PLUCKED STRING INSTRUMENTS

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Abstract

Robotic excitation systems for string instruments typically rely on open-loop geometric calibration, where the exciter moves to fixed coordinates. While highly repeatable within a single session, this study demonstrates that this approach is insufficient for comparative, longitudinal testing that requires remounting instruments. To quantify remounting errors, a simplified electric guitar underwent 9 complete remounting iterations on a Cartesian robotic platform, with a plectrum sweeping 17 fixed Z-axis depths. Acoustic analysis of the string signals revealed that sub-millimeter mounting shifts and mechanical creep cause substantial reproducibility errors. This high inter-mount variability is driven by unpredictable shifts in the spatial threshold where the plectrum transitions from static friction to full release. Consequently, nominal depths yielded highly variable responses across remounts, with shallow plucks exhibiting a Coefficient of Variation (CV) from 14% to over 60% for both RMS Energy and Spectral Centroid. These findings indicate that geometric calibration fails to provide reliable comparative data, pointing towards a shift toward closed-loop methods such as acoustic feedback control.

Keywords: *robotic excitation, measurement reproducibility, guitar comparative metrology, plucked string instruments*

1. Introduction

Robotic and mechanised excitation systems have largely replaced human players in laboratory studies of string instruments, because they offer a pluck-to-pluck repeatability that neither performers nor simple manual rigs can match [1], [2], [3], [4], [5], [6]. These platforms underpin comparative research where instruments, materials, or excitation components are exchanged between otherwise identical measurement series. Most platforms rely on geometric, open-loop calibration, in which the exciter is driven to a predefined spatial coordinate that defines the excitation condition. The implicit assumption is that a repeated coordinate results in a repeated physical state. Studies utilising robotic platforms report a high level of repeatability of the produced excitations [1], [3]. The other side of this relation, the positioning of the instrument within the experimental setup, is rarely addressed.

This is crucial for plucked instruments, as acoustic outcomes are highly sensitive to initial plucking geometry. Plucking position [7], [8], plectrum thickness [9], [10], plucking angle [11] and the details of finger-string contact [12] all measurably alter the radiated sound. In earlier work on an acoustic guitar we showed that changing the plucking depth in steps of 192 µm produces measurable, perceptually relevant changes in nearly every analysed acoustic parameter [13]. This dependence is strongly non-uniform: below a threshold the plectrum merely slides over the string, while above it the string is fully engaged and released.

Comparative metrology cannot avoid such interventions. Studies that exchange instruments or components must dismount and remount the specimen between conditions. Long measurement sessions additionally accumulate slow drift from settling of the frame, atmospheric effects on wood and string tension, plectrum wear, and compression of vibro-isolating interface layers. That geometric positioning alone is insufficient under these conditions has already been stated qualitatively [14]. What is missing is the quantitative counterpart. The practical question is therefore: how large are the errors that geometric calibration accumulates across realistic remounting cycles, and how do they compare with the effects that comparative studies aim to resolve?

This paper addresses the question experimentally. A

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simplified electric guitar, deliberately shaped for best-case mounting repeatability, underwent nine complete dismount-remount cycles on a Cartesian plucking robot, with a full plucking depth sweep recorded after each cycle. The main contributions are: (1) a quantitative error map of feature variability versus nominal depth, (2) measurement of effective geometric offsets across remounts, and (3) contextualisation against reported effect sizes in guitar literature.

2. Experiment

2.1. Test rig and specimen

The measurements used a Cartesian plucking robot developed at the Department of Mechanics and Vibroacoustics at the AGH University of Krakow [3], [14]. It utilizes stepper-motor linear axes to position a rigid plectrum holder relative to the mounted instrument. The depth axis was measured to have a step size of $(39.9 \pm 0.8)\,\mu\mathrm{m}$. Plucking depths are reported as integer indices $d = 1, \ldots, 17$, with consecutive indices differing by exactly one motor step. A simplified electric guitar made of spruce, as designed in [15], was utilized for the experiment. It was chosen deliberately, as the rectangular body represents the best case for mounting repeatability. Real instruments, with curved and varied bodies, can only prove more difficult. The guitar was held by two rigid clamps, with a 10 mm layer of vibro-isolating polyurethane foam between body and clamps to decouple the instrument from the frame. The same piece was used throughout all iterations. The instrument mounted in the test robot is shown in Fig. 1.

A wound steel D'Addario 0.65 mm diameter (0.026 in) string was tuned to $f_0 = 146.83\,\mathrm{Hz}$. The string was excited with a 1.14 mm Dunlop Tortex plectrum (polyoxymethylene) bolted through its body to the holder and secured with cyanoacrylate adhesive against rotation. The strings vibration was captured synchronously by two magnetic pickups, a Seymour Duncan SSL-5L single-coil and an SH-4 JB humbucker, through a PreSonus Quantum interface on its high-impedance instrument input. Results below are reported for the single-coil channel, whose narrower magnetic aperture provides a more local sample of the string motion [16]. The humbucker channel is used in Section 3.3 as a cross-check.

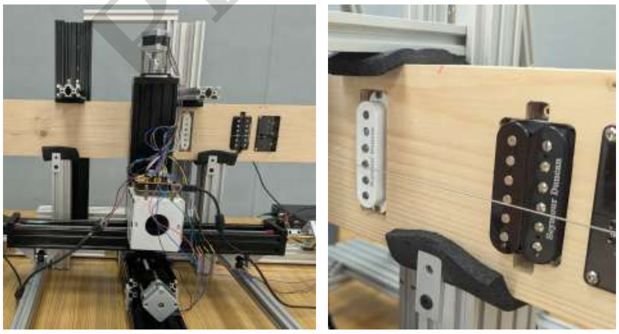

Figure 1: (Left) Measurement stand with the Cartesian plucking robot and the mounted specimen. (Right) Simplified guitar mounting in clamp with vibro-isolation.

2.2. Remounting protocol

The protocol simulated a comparative study in which measurements required repeated mounting and dismounting of the instrument. Nine independent iterations were performed on the same instrument without any change to its configuration or tuning. Between iterations the fixture was loosened, the instrument removed, and remounted following a standard procedure. Mounting repeatability was verified by eight caliper measurements along three axes between designated reference points on the instrument and the stand, at a resolution of 0.1 mm.

For every iteration, ten plucks were recorded at each of the seventeen depths, giving $9 \times 17 \times 10 = 1530$ plucks. Depth $d = 1$ corresponds to the plectrum barely touching the string and $d = 17$ to a pluck stronger than a musician's forte. This upper limit was chosen to reach the saturation regime observed in [13] while avoiding damage to the instrument or its dislodging from the fixture. After each pluck, 10 s of decay was recorded before the next plectrum movement, and the approach speed was set low so that the excitation was a clean pluck without an impact component, with the prolonged contact additionally damping any residue of the previous decay.

2.3. Acoustic features

Each recorded pluck was parametrised by twenty-one acoustic features covering energy (RMS energy, peak value, crest factor), spectral shape (centroid, bandwidth, roll-off, flux, flatness, skewness, kurtosis, high-frequency content), temporal behaviour (log attack time, temporal centroid, envelope decay slope, zero-crossing rate) and harmonic structure (tristimuli, odd-to-even harmonic ratio, inharmonicity, noisiness). The value of a feature for a given iteration and depth was taken as the median over the ten plucks of that series.

3. Results

3.1. Acoustic features across remounts

Figure 2 shows selected acoustic features as functions of the plucking depth. Every curve was produced by the same instrument, the same string and the same plectrum, differing only in that the specimen was dismounted and remounted between them.

All iterations share the same qualitative structure: a shallow regime in which the plectrum slides over the string and excites it weakly, a transition zone, and a saturating regime of full plucks. The spectral features shift through the transition and then stabilise, while the envelope decay slope changes from values near zero, characteristic of a short-lived friction transient, to about $-2\,\mathrm{dB\,s^{-1}}$, characteristic of a stable decay. The same was previously observed on an acoustic guitar recorded with a microphone [13]. Its independent reappearance here, on an electric guitar, indicates that it is a property of the plectrum-string interaction rather than of any particular instrument recording method.

The next observation is that the absolute positions

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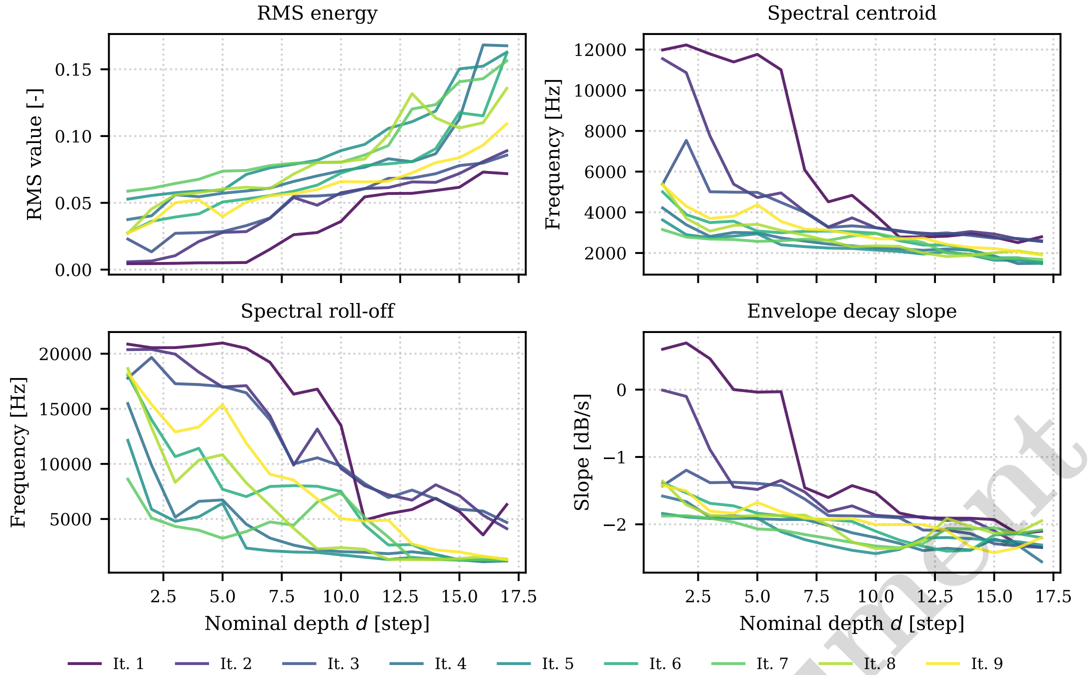

Figure 2: Selected acoustic features versus nominal plucking depth d for all nine mounting iterations (single-coil channel, median over the ten plucks of each series). All nine curves describe the same instrument in the same configuration differing only by a dismount and remount.

of the curves diverge markedly, and the first three iterations diverge in an ordered way. Iteration 1 is the strongest outlier in every displayed feature, with the lowest RMS energy over the whole depth range and, at shallow depths, a spectral centroid reaching about 12 kHz and a roll-off reaching about 21 kHz, which signifies a very low signal-to-noise ratio. Iteration 2 deviates in the same direction with smaller magnitude and iteration 3 even less so. This ordering is consistent with ongoing compression of the polyurethane interface. Fresh foam under repeated clamping cycles undergoes gradual permanent deformation, seating the instrument slightly deeper at every remount until the material stabilizes shifting the instruments position in relation to the plucker.

Finally, and decisively, the divergence does not stop once the interface stabilises. From iteration 4 onwards the offsets change sign and then scatter without trend. Iterations 5 and 7 show no sliding regime at all with their shallowest plucks already producing what the remaining iterations reach only at $d = 6$ and $d = 8$ respectively. This indicates that in these two mounts the sweep began beyond the transition threshold.

3.2. Effective depth offsets between remounts

The curves of Fig. 2 look like one common characteristic sampled from different starting points. This would point towards a shift between the position of the string and the calibrated plucking position, which causes each iteration to be shifted against one another. This hypothesis can be tested directly. For every iteration i a single shift value Δ_i along the depth axis was determined by minimising the mean squared difference between the shifted feature-depth curves of that iteration and a reference curve formed as the median of the remaining eight. The cost was summed over the normalised values of nine features at equal weights. One shift value is shared across all features as this would represent the physical hypothesis under test, since a rigid displacement of the specimen relative to the plectrum must move every feature together.

The quality of the alignment is expressed as the fraction of squared deviation from the reference that the shift removes, referenced to the unshifted curve rather than to a mean. For the measured curves its median across the nine iterations is 0.88. The absolute residuals are more telling: before alignment, the iterations deviate from their references by between 0.46 and 6.43 standardized units, and afterwards, every one of them lies between 0.18 and 0.45, so one number per mount removes almost all of what separates them.

Figure 3 shows the fitted offset values for each iteration in micrometres. They range from −311 µm at iteration 1 to 188 µm at iteration 5, a full spread of 499 µm, with a standard deviation across the nine remounts of 187 µm. Seven of the nine mounts are displaced by more than the 100 µm resolution at which their mounting was dimensionally verified, and the largest change between two consecutive iterations is 323 µm. Analyzing only remounts 4-9, which were made after the interface had stabilized, leaves a standard deviation of 87 µm and a spread of 211 µm, indicating that break-in does reduce the offsets.

These offsets should be read against two reference scales. Every mount was verified to within 0.1 mm at eight control points, yet the effective plectrum-string offsets inferred acoustically reached three times that value. The standard deviation of the offsets observed

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here was 187 µm, which is very similar to the 192 µm established in an acoustic guitar study as a depth distance at which sound responds measurably to a change in depth [13]. This means that a mounting procedure that passed a careful dimensional inspection still displaced the physically relevant geometry of the instrument by roughly one audible step, at random, with every remount.

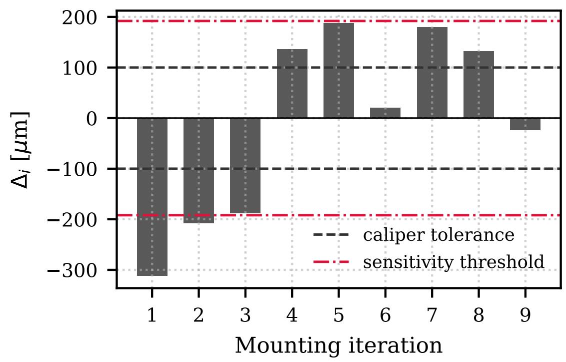

Figure 3: Effective depth offset Δ_i per mounting iteration. Dashed lines: the 100 µm resolution of the caliper positioning measurement. Dash-dotted lines: the 192 µm depth change shown to be measurable [13].

3.3. Repeatability at fixed nominal depths

To quantify repeatability the coefficient of variation is calculated using $\mathrm{CV} = \sigma/|\bar{x}| \cdot 100\%$. This is done at two levels: within series $\mathrm{CV}_{\mathrm{within}}$ which is computed over the ten plucks recorded at one depth within one mount and between remounts $\mathrm{CV}_{\mathrm{remount}}(d)$, which is computed at each nominal depth over the nine per-iteration medians. $\mathrm{CV}_{\mathrm{within}}$ and its median over all iterations and depths gives the noise floor attainable by this robotic plucker for this instrument regardless of remount calibration. $\mathrm{CV}_{\mathrm{remount}}(d)$ shows how faithfully a fixed coordinate geometric calibration reproduces a measurement.

The within-series noise floor confirms that the excitation mechanism itself is precise. The median $\mathrm{CV}_{\mathrm{within}}$ across the feature set is 3.1%, and for the energy and spectral-shape features that carry the comparison it lies between 2.7% and 3.1%. Seven features exceed 4%, with spectral flatness being the worst at 14.4%, which flags those as intrinsically noisy and limits the conclusions that can be drawn from them. Figure 4 presents $\mathrm{CV}_{\mathrm{remount}}$ against the nominal depth, and Table 1 summarises the feature set. The variability is large and strongly depth-dependent. At lower depths across the sliding and transition zones, the CV of RMS energy spans 18-63% and that of the spectral centroid spans 14-64%. This is due to the remount errors sampling at a less stable section of the instruments dynamic range. Additionally, the issue cannot be solved by choosing the best coordinate. At its most favourable depth RMS energy still returns 18.3% against a floor of 2.7%, and the spectral centroid 13.7% against 3.1%. Finally, the optimum depth for repeatability is feature-specific, with minima falling anywhere between $d = 1$ and $d = 17$. A plucking depth can be chosen to minimize the variability for a subset of features but no single solution exist for all features.

Repeating the analysis on the six more stable mounts roughly halves the CV values with RMS energy falling to 10.5% at its best depth and the spectral centroid to 7.8%. Preconditioning the vibroisolation material would help limit variance but would not resolve the problem. Recomputing the headline figures with each iteration removed in turn moves them by 2.7 percentage points at the median, with RMS energy staying between 16.1% and 19.6%, so no single anomalous mount is responsible for the observed results. The observed variance is not equally distributed across all features. Energy and spectral-shape features exceed 10% between-remount CV at essentially every depth, whereas temporal descriptors are far less affected. Analysis of the humbucker recordings reproduces the same pattern but at a lower magnitude. The depth dependence of $\mathrm{CV}_{\mathrm{remount}}$ agrees between the two channels (median Spearman correlation 0.76), yet the minimum achievable CV differs between them by up to a factor of seven, in both directions depending on the feature. The choice of pickup itself changes which features appear as repeatable.

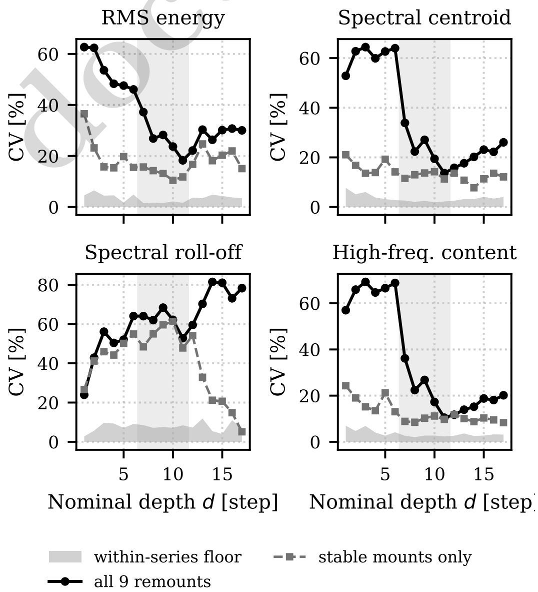

Figure 4: Coefficient of variation $\mathrm{CV}_{\mathrm{remount}}$ at depth d (solid), against the median within-series floor (shaded) and the same $\mathrm{CV}_{\mathrm{remount}}$ computed for remounts 4-9 after the vibro-isolating interface stabilised (dashed).

4. Discussion

The irreproducibility observed here has two interacting components. The effective plectrum-string engagement point drifts between remounts by an amount on the order of 0.2 mm, and the sound of the instrument responds to plucking depth most steeply around the transition from frictional sliding to full release. A fixed coordinate therefore samples an unpredictable part of that transition at every remount, which is where Fig. 4 concentrates its variance. The consequence for measurement practice is that within-series precision

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Table 1: Repeatability per feature. The median within-series CV, and the minimum and maximum between-remount CV over the seventeen nominal depths, with the depth in parentheses.

Feature	$\widetilde{\mathrm{CV}}_{\mathrm{within}}$	$\mathrm{CV}_{\mathrm{remount}}$ range [%]
RMS energy	2.7%	18.3 (11)-62.7 (1)
Peak value	4.3%	30.3 (16)-48.3 (9)
Spec. centroid	3.1%	13.7 (11)-64.4 (3)
Spec. bandwidth	1.5%	8.3 (11)-15.7 (6)
Spec. roll-off	7.7%	23.9 (1)-81.5 (14)
Spec. flux	7.5%	44.4 (17)-62.1 (7)
High-freq. content	2.9%	10.5 (11)-69.3 (3)
Log attack time	1.7%	1.5 (8)-16.1 (17)
Env. decay slope	1.7%	4.2 (16)-40.2 (6)
Zero-crossing rate	4.8%	9.2 (11)-143.3 (6)
Inharmonicity	3.3%	6.7 (16)-56.4 (5)
Odd/even ratio	3.5%	5.2 (10)-15.3 (1)

does not entail between-configuration accuracy: the excitation mechanism used here is precise to about 3 %, and that value does not answer whether two series recorded on either side of a remount are comparable.

Whether a scatter of this size matters depends on the magnitude of the effects that comparative studies are trying to detect. To assess this, a set of studies was investigated with regards to the size of reported results. The values that follow come from studies using different instruments, recording methods and analysis choices, so they are quoted to establish an order of magnitude rather than to support any direct comparison. Additionally, none of these results are called into question here. On spectral centroid, four body woods differ by about 15 % [15], four sound hole configurations by about 8 % [17], and active vibration control of the top plate by about 4 % [18], all three described in their sources as clearly audible. Remounting alone, with no change to the instrument, produces 14 % at the depth most favourable to repeatability. Dispersions of the same order arise between instruments that are nominally identical: across six guitars built by one maker to a single specification, the quality factors of the three principal body modes vary by 9, 20, and 30 %, a spread their authors attribute largely to manufacturing rather than wood variability [19].

Variability of this size is nevertheless present, and unmeasured, in the studies it would affect. Replication in this literature stops at the excitation: the specimen is mounted once per condition, a series of excitations is recorded, and their spread is reported. None of the studies surveyed here, comparative work and excitation-method development alike [1], [2], [3], [4], [5], [6], [15], [17], [19], measures what a remount does. The concern surfaces occasionally, with one study concluding by recommending care during configuration changes [20], but it stops there. Going further requires a different study design. An experiment that mounts each condition only once has no way of seeing how much the mounting varies. From inside a single session this variance is invisible. A displaced series is internally consistent, and nothing in the measurement indicates that the excitation has moved.

When a condition requires remounting, plucks repeated within one mount cannot show what the remounting did. Each condition has to be recorded across several independent mounts. This will usually widen the reported uncertainty rather than narrow it, and the wider figure is the honest one. A stiffer fixture is not the solution either. Stiffer mounts couple the specimen to the frame, and clamping an instrument tightly enough to hold it to within the sensitivity threshold would load the body and change the quantity being measured. The compliance that protects the measurement is the compliance that creeps, and our results show that it cannot be conditioned away. The scatter fell from 187 µm to 87 µm, but did not disappear or become predictable.

Several things bound the numbers, though not the direction of the result. The experiment covers one instrument, one string, one plectrum and one fixture, and the rectangular specimen, chosen for its ease of mounting, means the achieved values are more likely a floor than a ceiling. The reported offsets are inferred from the sound rather than measured. What supports the inference is how well it works, but it remains an inference. The caliper check, at 0.1 mm across eight points, cannot see where the plectrum actually meets the string. Nine mounts is a small sample, so the analysis leans on the patterns across depths and features, and on the leave-one-out check, rather than on any single value. How large the variation looks also depends on which pickup is read, as the humbucker shows the same pattern, but the lowest values it reaches differ from the single coil's by as much as seven times.

5. Conclusions

This paper tested geometric calibration across nine complete dismount-remount cycles of a simplified electric guitar, mounted under conditions chosen to be as repeatable as possible. Every mount passed a dimensional check, and the plucker repeated itself to about 3 % within a series. The plectrum still landed in a different place at every mount, with a standard deviation of 187 µm across the nine. A mounting procedure that passed careful inspection therefore moved the instrument by roughly one audible step, at random, every time. Because the sound changes so sharply around the point where the plectrum stops sliding and releases the string, that scatter shows up as variation between remounts of 14 to 64 % for basic energy and spectral features, three to seven times the within-series floor even at the best depth.

A measurement can be precise within itself and still not be comparable to the one taken before it. Nothing inside a single session shows this, and no fixture removes it. A potential solution to this issue is closed-loop calibration that finds the string or calibrates to a behaviour of the string-plectrum system, instead of trusting a coordinate. The design and testing of such an approach are the subject of forthcoming work.

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