A TMR Angle Sensor for Gesture Acquisition and Disambiguation on the Electric Guitar

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ABSTRACT

This paper presents a novel approach to the acquisition of musical gestures on guitar based on Tunneling Magnetoresistance (TMR) sensing. With this minimally invasive setup, tracking of the horizontal displacement of the strings is used to capture gestures related to left and right-hand techniques. A pitch-based calibration is suggested to map the sensed displacement to pitch shifts so that the acquired signals can be directly used to estimate pitch produced by string bending in real-time. Some of the performer's gestures, despite corresponding to different physical interactions, might produce a similar sonic output, as is the case of upward and downward string bends on the guitar. The proposed technology can be used to disambiguate between these gestures whether that is for automatic transcription purposes or for crafting instrument augmentations that build upon the performer's existing expertise.

CCS CONCEPTS

• **Hardware** → **Sensor devices and platforms**; • **Applied computing** → *Sound and music computing*; • **Performing arts**; • **Computer systems organization** → Embedded systems;

KEYWORDS

multi-modal guitar, angular sensing, audio analysis, tunneling magnetoresistance, musical gestures, playing techniques, gestural ambiguities, string bending

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1 INTRODUCTION

The electric guitar might be one of the most ubiquitous instruments from the 20th century. The instrument has been embraced and adapted by a wide range of musical traditions [3, 5], leading to idiomatic playing styles that carry both stylistic elements and expressive techniques. As a result, a gestural palette has been developed that contributes to shaping the identity of the instrument by conveying not only musical meaning and articulation, but a signature that allows us to recognise genre and even particular personal styles and instruments [25].

> Indeed, the manner in which you play an instrument can transform both the instrument itself and the nature of the musical sounds produced.
>
> —Paul Théberge, 1997 [30]

However, capturing these expressive gestures – whether that is for musical information retrieval (MIR) or instrument augmentation – poses a series of difficult challenges. The flexibility of left- and right-hand techniques, the instrument's inherent polyphony and the different nuances associated with the combination of *excitation* gestures (e.g. plucking) and *modification* gestures (e.g. fretting, string bending, vibrato, etc) make the extraction of musical parameters from the audio signal produced by the instrument a complex task. Moreover, some of these gestures, despite being associated with different physical interactions and perhaps presenting different significance to the performer, might have similar, even identical, sonic results and therefore be virtually indistinguishable from this perspective. For example, left-hand gestures that control vibrato might be indistinguishable from other pitch-related articulations, and different picking movements might produce the same sonic result (see section 2.1 for more details and examples).

One potential solution that might provide the kind of nuanced analysis required for the study of expressive gestures is the use of complementary direct sensing methods that provide measures related to the physical features of the performer's actions.

In this work, we present a novel application of Tunneling Magnetoresistance (TMR) sensors for tracking the horizontal displacement of a ferromagnetic string, which can be used to capture different dimensions of playing and disambiguate gestures that have similar sound signatures. We analyse how this sensor can be easily calibrated based on pitch contour estimation and show potential applications for music transcription and instrument augmentation where the performer's expertise is repurposed for expanding the gestural possibilities of the instruments.

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2 BACKGROUND

2.1 Gestural ambiguities and the projection model

The *projection* metaphor proposed by Jack et al. [13] offers an interesting framework for understanding the coupling between performer and instrument. Based on the hypothesis that only meaning-bearing movements result in an audible effect, the authors present a model in which actions projected through the instrument pass through a point of reduced dimensionality before being expanded out as sonic and kinematic behaviours. The instrument's *bottleneck* determines the bandwidth of interaction (the multiple degrees of freedom concerning musician's movements) that are rendered into musically meaningful outcomes. By engaging with the instrument's projection, instrumentalists develop multiple patterns of interaction (*choreographies*) which represent their idiomatic gestural space.

Under this scope, we can analyse some of the ambiguities inherent to expressive guitar playing techniques. Due to the morphology of the instrument, the same outcomes can be achieved via different mechanisms: a *vibrato* effect can be produced by moving the finger pressing the string in parallel to the string's axis (longitudinal) or by bending the string perpendicular to its axis (axial); *trills* (rapid alternations between two consecutive notes) might be performed by either using *slurs* (hammer-on/hammer-off alternations) or *portamento* within adjacent frets; smooth transitions between notes can be realised via string bends or *glissando*. The sonic result emerging from many these techniques, although not identical, can be very hard to distinguish and transcribe [29].

String bending provides another example of how an instrument's bottleneck leads to different gestures producing the same sound. Due to the physics behind string stretching [10], the pitch of the played note will always be raised regardless of the bending direction (up or down). Furthermore, techniques like *pre-bends* (where the string bent before plucking to perform a downward pitch shift), do not have an immediate sonic effect and can only be analysed after the whole event has occurred.

Yet another example of this scenario is the picking direction and the different techniques that derived from it (*sweep picking*, *cross-picking*, *tremolo picking*, *downpicking*, etc). Although these techniques play an important role in the guitarist's repertoire, the downward and upward picking movements are virtually indistinguishable from a sonic standpoint.

A system enabling gesture disambiguation could not only help us better understand the performer's approach to their instrument and performance techniques, but also help us design new augmentations that exploit these gestures for extended techniques. Such augmentations could provide a greater level of control intimacy without encumbering performer's experience, allowing them to quickly adapt to these and to achieve a high degree of virtuosity and effectively expanding the instrument's *bottleneck*.

2.2 Direct Gesture Acquisition

The use of sensors for capturing expressive gestures during performance has been a staple of certain DMI (Digital Musical Instrument) design trends in recent years.

McPherson et al. [20] analysed the constraints of keyboard playing techniques and designed an augmentation mechanism based on capacitive sensing that built upon interactions which would not interfere with traditional technique to enable additional control of pitch. They highlight the importance of using new sensor modalities to create interfaces which repurpose existing user expertise in order to retain access to virtuosity.

Based on similar principles, other instruments have been objects of study and experimentation for capturing performance parameters. Bow movement tracking for members of the violin family has been analysed extensively, with some of the most relevant examples being the *Hyperbow* [32], which employed a combination of sensing techniques to extract different dimensions of bow movement in real-time, and the work of Pardue et al. [24] where linear position sensors located on a violin's fretboard were used to assist audio-based pitch tracking, while bow tracking was performed via optical sensors to detect note onsets.

Kapur et al. [14] presented the *ESitar*, an electronic sitar controller that used a variety of sensors to generate MIDI control signals for sound manipulation. These sensors ranged from FSRs that captured thumb pressure on the *mizrab* (plectrum) to a resistor network connected to the frets to estimate pitch which was also combined with a pitch tracking algorithm.

More specifically on the guitar, the scope for gestural analysis has mainly been focused on left-hand and right-hand techniques separately. Guaus et al. [11] employed capacitive sensors attached to the frets of a guitar to extract basic left-hand gestures, but due to cross-talk, noise and a low sampling rate, their system was not suitable for complex articulations nor was it able to discriminate between strings. Biral et al. [4] explore the possibilities of pressure sensing to analyse the effects of different types of picking and palm-muting gestures on the electric guitar.

More recently, Vets et al. [31] proposed a system that focused on capturing picking gestures to design musical applications without adding extra cognitive load and which built on established sound-to-gesture relationships. Their *PLXTRM* system encompasses a modified guitar bridge, a guitar pick with capacitive sides, a 3-axis accelerometer and a hexaphonic pickup. This apparatus was employed to predict different picking patterns and other performative aspects regarding the player's right hand.

Also focused on right hand movements and motivated by the search for high resolution, low latency and high bandwidth interactions, Morreale et al. [21] presented a minimally intrusive augmented pick that exploited movement with respect to the permanent magnets in electric guitar pickups to generate control signals related to the pick's motion. These signals were then used to create nuanced interactions with sound that coexist with traditional plucking techniques.

Similarly, Freire et al [9] employed an Inertial Measure Unit (IMU) together with a hexaphonic setup to capture and characterise right-hand strumming gestures. The authors compared their results to those from a high-performance optical motion capture system and concluded that the proposed approach can offer a similar refined control for use in DMI augmentation while retaining characteristics that make it more appealing to use as compact wearable device.

Our proposed system builds on these ideas to present a real-time tracking system for measuring horizontal string displacement on the electric guitar that could potentially be easily retrofitted into any electric guitar as another 'pickup' and used to design augmentations that do not interfere with the player's existing technique. This technology has the potential of being able to capture performance parameters related to both the left-hand - such as string bends and vibrato - and the right hand - plucking direction and intensity - and can offer tracking over multiple strings either in combination with a hexaphonic pickup or a more traditional setup.

2.3 String Bending

String bends (stretching of the guitar string to change pitch of played notes) are used across many different styles of guitar playing. This technique allows the player to exert continuous control over the pitch of a sounding note and provides a mechanism to add vocal-like qualities to guitar soloing and explore microtonality.

Although the physical phenomena associated with string bends [10] and their effects on an audio signal have been studied in detail, being able to capture the movement of the string in real-time with a minimally intrusive setup poses a real challenge.

A few commercial attempts have been made to extract real-time string-bend information, but only some of them focus on direct sensing of the string's movement. The *SynthAxe* for example (a guitar-like synth instrument designed in 1985) relied on a series of coils embedded in its fretboard to detect string movement (two per string) [1], but it only worked in monophonic mode and the instrument used a separate set of strings for left and right hand, where the fretting hand was used only for pitch selection. Another 80s MIDI controller, the *Yamaha G-10*, employed optical shutters embedded in its tailpiece to account for string bend. More recently, in 2011, the German company M3i Technologies GmbH developed, in conjunction with Fraunhofer University, a tailpiece coated in a piezoresistive thin film to capture string bends[1] but this technology has not been made available (to the best of our knowledge). Other novel techniques include the use of microflex sensors (strain gauges) underneath the guitar saddles to detect variations in string tension, as in the *Industrial Radio Solange 6 Midi Guitar*[2] or inductive sensing coils on the saddle that, used as part of an oscillator circuit, can detect inductance changes associated with string displacement, as proposed by Keith McMillen for his *Stringport 2* system [17].

Most of these approaches, however, either involve the design of completely new guitar-like instruments or do not offer information regarding the string's direction of movement. As an exception, Freed et al. proposed in [8] a dual-axis reluctance sensor for detecting string vibrations over its two axes of motion, but their prototype struggled with cross-talk between strings and, to the best of our knowledge, no musical applications have been further developed in the published literature.

2.4 TMR Angle Sensors

Magnetic sensing has been at the core of guitar technology since the invention of the electric guitar. The pickups used on most electric guitars are effectively variable reluctance sensors that translate the vibration of the string into voltage as it creates changes in the magnetic flux as the string is magnetised [12]. Recent developments in magnetic technologies such as those based on Hall or magnetoresistive (MR) effects[3] present some interesting alternatives that, while still working with magnetic principles and therefore being suitable for traditional electric guitar designs, would allow extracting a more accurate representation of string movement.

Tunneling Magnetoresistance (TMR) sensors in particular belong to a particular family of highly sensitive, low power MR devices that exploit the phenomenom by which electrons have a magnetic moment (spin) which has a specific direction based on how materials are magnetized [7]. TMR devices are constructed from magnetic tunnel junctions (MTJ) with a spin-valve structure where two ferromagnetic layers are separated by a thin insulation barrier that ensures magnetic coupling to occur so that electrons can tunnel between these. The tunneling current of electrons depends on the relative orientation of the magnetic field on each layer so it is usual to set one of the magnetic layers as a reference by fixing (pinning) the direction of magnetisation so that the 'free' layer acts as the sensing element, aligning its magnetisation with the applied field [26]. Most available TMR sensors are built in a bridge configuration with two or more MTJ elements with perpendicular pinned directions to minimise noise and temperature drift. Combining multiple bridges pinned 90^o with respect to each other can be used for capturing the rotation of the magnetic field.

Magnetoresistive sensors and, more specifically, TMR sensors have successfully been employed in place of inductive guitar pickups to detect string vibrations outperforming these in terms of external field rejection, sensitivity and frequency response flatness [16]. Khan et al. [15] applied an AC constant current source to a ferromagnetic guitar string to generate a magnetic field that could be sensed by a TMR angular sensor to characterise the vibration of a guitar string. The sine and cosine rotational sensed components were then processed by a differential amplifier to obtain an amplitude modulated signal, filtered and amplified, with the output demodulated to measure the vertical displacement waveform caused by oscillation. Although this technique could allow eliminating cross-coupling effects by using different modulation frequencies per string, it involves a complex setup that adds undesired non-linearities and requires inducing currents greater than $100mA$ in each string, which could cause unwanted effects such as heat dissipation and material degradation.

3 TECHNOLOGY: TMR BEND SENSOR

3.1 Bend sensor setup

The sensor we employed in our design belongs to the same family as the one used in [15], NVE's AAT00X series[4]. These miniaturised TMR angular sensors contain two perpendicularly-pinned half-bridge resistive elements that provide signals proportional to the 2D angular components of a saturating magnetic field in the sensor plane. They offer two sinusoidal outputs for sine and cosine components with a typical peak-to-peak signal level of $200mV/V$

[1]https://www.fraunhofer.de/en/press/research-news/2011/july/guitar-and-computer.html
[2]https://industrialradio.com.au/products/solange-6-midi-guitar/

[3]Magnetoresistive sensors work under the principle that ferromagnetic materials experience a change in electrical resistance under the effect of an external magnetic field.
[4]https://www.nve.com/angleSensors.php

and supply voltage of up to 5.5V with robustness against air-gap variations. The AAT001-10E [23] sensor that we used has a typical output impedance of $625k\Omega$ and is as capable of detecting magnetic field variations down to $30Oe$ ($2.4kA/m$) strength.

In our setup, the TMR sensor lies underneath the guitar string with its sensing plane (xy) parallel to the string's radial axis and perpendicular to the main axis of vibration (z, see Fig. 1a). With x being orthogonal to the string longitudinal axis and y parallel to it. The string is magnetised by two axially-polarised neodymium magnets that are positioned equidistant from the sensor's centre along the string. Both magnets share polarity so that when the string is magnetised and stationary in the x axis the magnetic flux saturates the TMR sensor, offering a constant DC offset reading. When the string is plucked or bent so that a displacement is provoked on the non-fixed end of the string (see Fig. 1b), the magnetic flux is shifted along the x axis and the sensor is able to capture the change of direction of the magnetic field. Although the TMR sensor measures rotation, since both the string and the magnets are not moving on the y axis of sensing, the horizontal motion of the string can be derived from the motion of the field on the x axis. Using simple trigonometry we can infer that the horizontal displacement will be proportional to ratio of the *sine* and *cosine* outputs of the sensor: $d_x \propto V_{sin}/V_{cos}$. The direction of movement can then be obtained using the DC offset of the resting string as a reference.

After experimenting with different N42 neodymium magnets, we settled on N42 4x3mm magnets with pull force of 0.54kg set 9mm apart from the centre of the TMR sensor. Both magnets and sensors were set at a vertical distance of 4mm from the resting string. Each pair of magnets corresponding to one string shares the same polarity. Magnets for adjacent strings have inverted polarity to minimise interference and cross-talk from adjacent strings and increase the detection range.

To acquire these signals with the best possible SNR and resolution, the cosine and sine outputs are amplified independently using a low-power operational amplifier in non-inverting configuration with a gain of $A_v = 3$ as suggested in the manufacturer's datasheet. Both sensor and amplifier were powered from a $+5V$ rail.

We digitise these signals with a 16-bit SAR ADC available on the Bela embedded platform [19]. Bela was chosen in order to gather sensor data together with audio signals from the instrument at audio rate and in a sample-aligned manner without jitter. A diagram of the complete prototype sensor setup together is shown in Figure 2, including details of the sensor prototype. Design files for the sensor kit are available on the supporting website.[5][6]

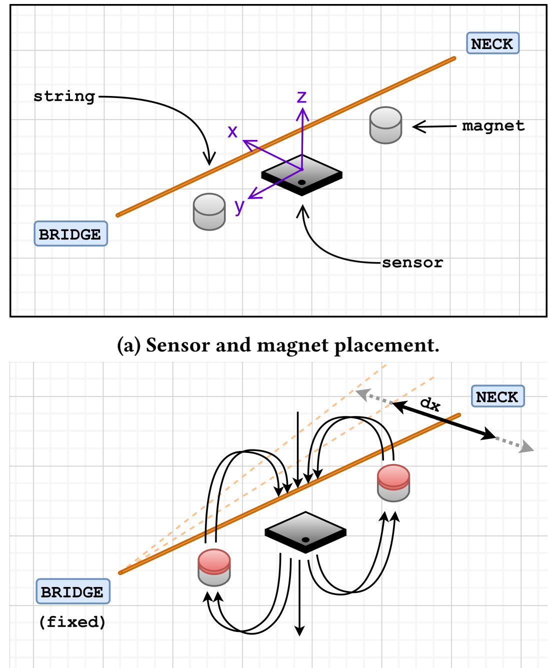
3.2 Characterisation

NVE's AAT00X sensors provide good linearity and negligible hysteresis [28] but these assumptions can only be trusted under the effects of a saturated magnetic field and might not hold true under the conditions of this experiment. The alignment of the sensor with respect to both magnets and the string is critical to obtain a usable range. Moving the sensor closer to the string increases the sensing range but can produce non-monotonic response at maximum string bend, while positioning the magnets closer to the strings can result in range saturation when the string moves vertically (on the z axis). Furthermore, we appreciated an existing trade-off between monotonicity and dynamic range: if the sensor is positioned closer to the guitar's neck, where the displacement caused by bending the string is higher, the string might stop being magnetised when moving outside the range of the neodymium magnets, causing a voltage drop at the edges of the movement. Positioning the sensor closer to the guitar bridge minimises these issues while offering a sensing range of about $1V$ peak-to-peak.

Figure 3 shows the estimated displacement caused by different expressive left-hand gestures (up/down *bend* and *radial vibrato*) compared to pitch contours extracted from the corresponding audio signals. This demonstrates that the sensor arrangement can be used to infer not only the direction of the transverse movement, but an approximation of pitch shift caused by such movement. For a more elaborate description of how the mapping was performed see section 3.2.1.

The V_{sin}/V_{cos} plots of Figure 3 show some apparent hysteresis on the sensor readings, as the estimated displacement does not return to its initial value directly after the bend is performed. We suspect that this is related to the inherent magnetic hysteresis caused by the magnetisation of the string [6] and not to the sensor itself, but this effect requires further investigation.

This setup is capable of capturing other performance parameters concerning the horizontal (x axis) displacement of the string. Figure 4 shows the detection of plucking events that correspond to the onsets of several notes. Lower peak heights correspond to softer dynamics while higher peaks indicate louder dynamics. The picking



(a) Sensor and magnet placement.

(b) Magnetisation and displacement of a guitar string.

Figure 1: Sensor setup and placement for one string.

[5]http://instrumentslab.org/research/bend-sensor-tmr.html

[6]Bend sensor design files: https://github.com/adanlbenito/bend_sensor_breakout/

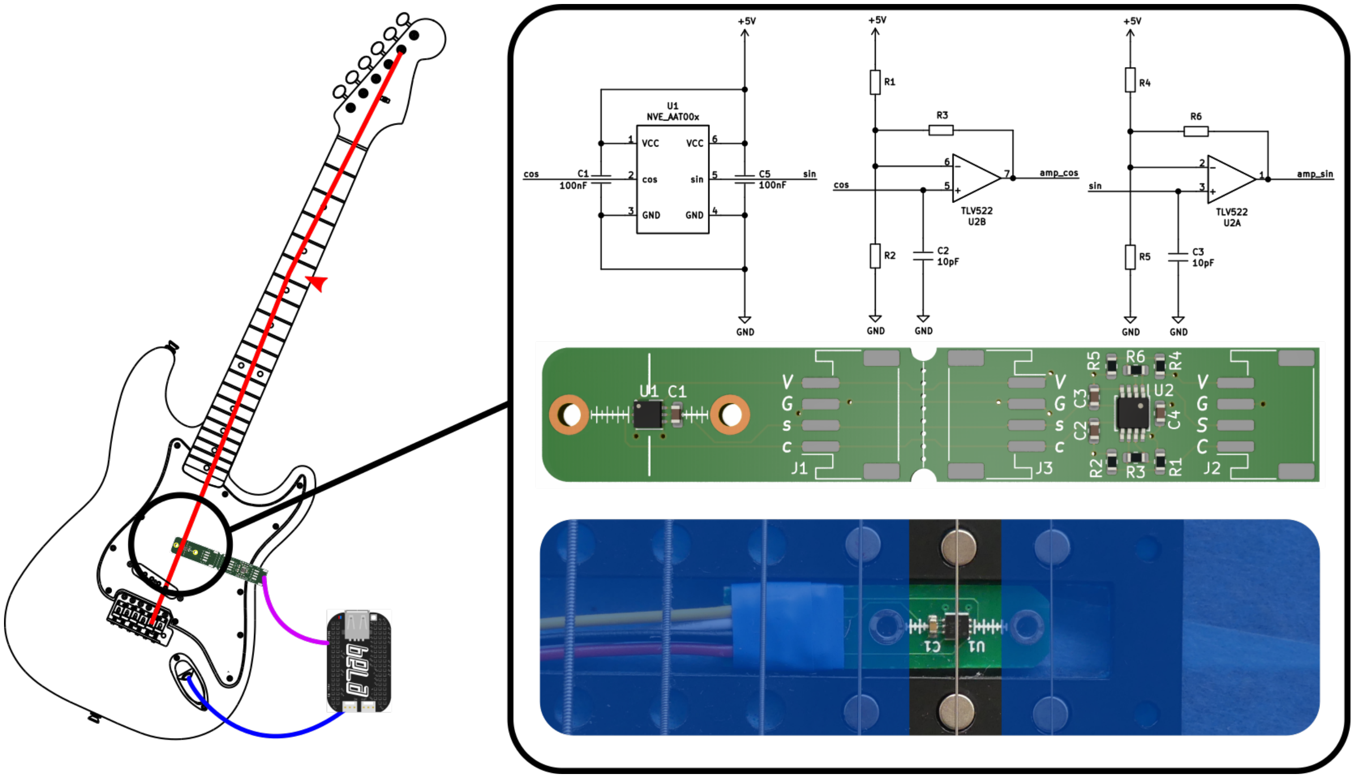


Figure 2: Diagram of the complete testing setup for estimating bend on one string. Figure on the right shows a render of the prototype PCB and schematic together with a close-up photo of sensor.

direction (upstroke/downstroke) is indicated by whether the peak is positive or negative with respect to the resting value.

3.2.1 *Pitch-based calibration.*

Although the sensor could be characterised directly in terms of string displacement and bend angle (as suggested in [15]) and pitch changes estimated analytically from physical models of a string under tension [10], this would be complex to implement and calibrate. Instead, we take an empirical approach comparing sensor readings to audio pitch tracking on a calibration dataset. By fitting a simple model to the pitch contour of annotated data, we can obtain a direct mapping that can be used to estimate pitch caused by string bends in real time. This approach has the advantage of relating sensor data directly to musical parameters, but also offers an intuitive, straight-forward approach to calibration that could easily be replicated when installing the sensor on different instruments.

For this purpose, we captured a synchronous audio stream together with the amplified sensor signals for a series of different bends on one string performed over the same fret both in the upward and downward direction as well as the DC offset reference signal of the string in resting state (equilibrium).

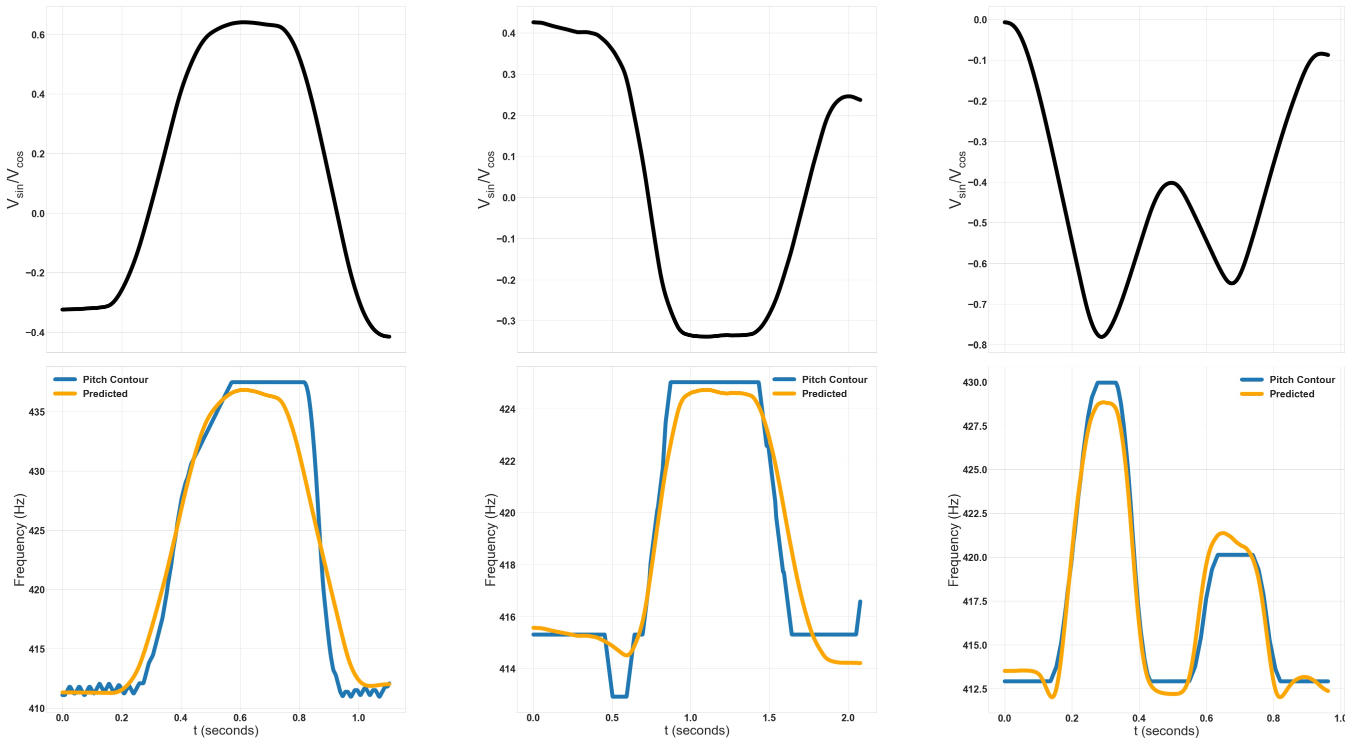
Pitch contours for the acquired audio signal are extracted using the Melodia algorithm[7] [27] and non-voiced components are filtered out. The voiced segments of the pitch contour were further segmented into single note events using 'island building' and RMS power thresholding [18]. Note segments were then aggregated within a window of 100ms to find note groupings corresponding to articulation segments.

The estimated string displacement was computed from the sine and cosine components from the sensor signals and the result filtered via a centred moving average to reduce noise. The DC voltage captured when the string is stationary is used as a boundary to separate upward and downward movements (positive and negative over the x axis).

A mapping between the estimated displacement and pitch shifting was then produced for each set of movements via quadratic regression. The resulting 2^{nd} order polynomial maps displacement to frequency. Figure 3 shows some example results of this calibration process for both upward and downward string bends and axial vibrato. Although the fit is not perfect, we can see how the direction of movement can be easily inferred from the sensor data alone and its contour used to approximate pitch shifts.

One caveat of this approach is that, since the pitch shift produced by a bend depends on how much the string is stretched, same

[7] Different options were evaluated such as the YIN and Praat, which tend to provide smoother pitch contours, but Melodia was used here for convenience as it seemed to work better for pitch contour segmentation.



(a) Upward Bend **(b) Downward Bend** **(c) Vibrato**

Figure 3: Estimated displacement of the string under different left-hand gestures (top row). Bottom row shows the estimated pitch contour using *Melodia* against predicted values obtained by remapping displacement.

shift amounts on different frets will result in different bending angles and therefore different displacements measured at the sensor location [10]. A pitch-dependent piecewise mapping (repeating this process for each string and fret) would be necessary to obtain a more accurate representation.

4 APPLICATIONS

Here we discuss some potential applications of this technology that could benefit from its unobtrusive characteristics and low cost.

4.1 Enhanced Transcription

As it has been presented on the previous section, the proposed sensing arrangement allows us to track the horizontal displacement of the string (dx) at a point over its longitude. Such displacement is usually associated with two sets of gestures in guitar playing: the excitation (i.e. *plucking*) of the string and the pitch manipulation caused by bending it, whether that is to achieve a *vibrato* effect or smooth pitch shifts or *glides* between notes. Transcribing these articulations usually involves looking at the pitch contour and envelopes of a solo recording and tracking their evolution over long-term windows. Moreover, techniques that involve transition between notes or note groupings can result ambiguous from this perspective. Combining classic MIR techniques with the information provided by these sensors can help resolve such ambiguities and minimise errors. In addition, it can provide extra information to annotate aspects of musical gestures that wouldn't be detected otherwise, such as the plucking or bending direction.

4.1.1 *Bend Direction.*

Detecting string bends requires differentiating between pitch shifts produced by this gesture and other techniques such as *slides* in between notes and is still somehow an open challenge for purely audio-based MIR techniques [29]. Besides, the problem becomes even more complex for vibrato, which in the guitar can be produced by either longitudinal or radial movements.[8] Furthermore, certain gestures used to manipulate pitch come before the production of sound, as it is the case of *pre-bends* employed to produce smooth pitch variations from a higher note to a lower one.[9] Our sensing setup can provide ground-truth values that would minimise annotation errors and, in addition, be used to include labels regarding expressive gestures that would be impossible to have without the extra information (such as the bending direction).

Here we describe a simple method that can be followed to obtain rough annotations of string bends based on sensor data. We first extract the pitch contour for the different articulation segments from the audio recordings obtained following the procedure described in Section 3.2.1 and the corresponding time segments from the

[8]Axial vibrato is performed by rocking the finger backwards and forwards along the the string axis while radial vibrato involves bending it perpendicularly to its axis.
[9]To produce a downward shift in the guitar at the attack of the note, the player needs to bend the string before it is excited and then release.

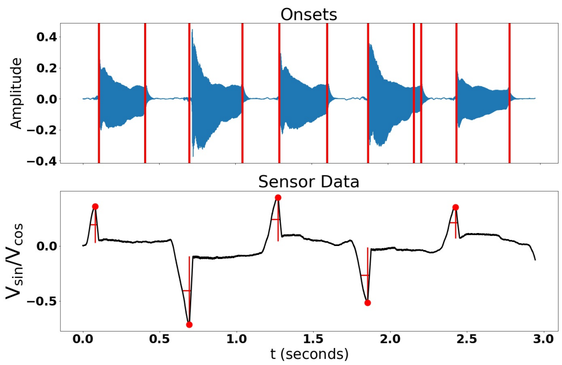


Figure 4: *Complex domain*[2] onset detection against peaks of the rescaled sensor signal for an alternate picking section. Red lines on the top graph indicate the detected onsets on the audio signal while dots on the bottom graph indicate peak locations on the sensed data.

approximate string displacement derived from the sensor signals. For each note within the segment, a linear approximation via least squares regression is obtained for both the pitch contour of the note and the associated displacement, obtaining a slope estimation for each. Notes for which the absolute value of the displacement slope exceeds the threshold value (obtained experimentally but ultimately a parameter of the algorithm) can be labeled as *bend notes*. The direction of the bend can then be extracted by comparing the sign of the slope for both sets of data: if contour and displacement slopes have the same sign then the note corresponds to an *upward bend* (if positive) or *release* (if negative). If the slopes have opposite signs then the bend happened *downwards* and the sign of the contour slope indicates whether it is a *bend* or a *release* event.

4.1.2 Plucked Onsets and Picking Direction.

Identifying onsets in guitar recordings is also an interesting problem that could benefit from our setup. Onsets on the guitar can be produced by a great range of gestures not necessarily associated with plucking the string (i.e. *hammer on/off*, *tapping*, etc.) and can have either percussive or pitched qualities [22]. By annotating plucked onsets we help narrow down the scope of onset detection algorithms. We exemplify this by contrasting onsets detected by common detection methods (HFC, Complex domain, Spectral Flux, etc.) [2] with local positive and negative peaks detected from the centered displacement values (shorter than 100ms). A peak that matches the position of an onset (within a given error margin) can be considered a plucked onset. The peak sign gives an indication of whether the string has been plucked up or down, which could be of importance for extracting picking patterns, and the height of the peak, associated with the amount of displacement, could be considered proportional to the intensity of the excitation and compared against the amplitude values at the onset location. Figure 4 shows a comparison of onsets detected via the *Complex Domain* method [2] and peaks from a segment of alternate picking notes.

4.2 Augmentation

Bending a string up or down on the guitar has the same sonic effect: a smooth upwards pitch shift. Using the technology we proposed here, we could expand the control possibilities of the instrument while exploiting performer's expertise in a way that actions are not encumbered by these new affordances. The sensed horizontal displacement of the string associated with bending gestures can be exploited to disambiguate between different actions with similar sonic outputs and produce augmentations that extend traditional playing techniques.

4.2.1 Extended Pitch Control and Disambiguation.

As discussed in Section 3.2, by following a simple mapping between pitch contours and displacement data derived from the sensing outputs of the TMR sensor, we can accurately estimate the pitch shift produced by a string bend using the sensor data alone. This has the potential of enabling manipulation of the traditional pitch control mechanisms available on the electric guitar. The augmentation described below makes use of this estimation to change the rules of string bending based on bend direction therefore expanding beyond the physical constraints of the instrument.

By employing a real-time pitch tracking algorithm in combination with this information, we can generate pitch estimates for the notes produced by a bend without adding further latency. We prototyped an instrument combining our sensors with the Bela platform that employs a real-time YIN pitch detection algorithm as described in [24] for pitch detection with a window size of 512 samples and a hop size of 16 samples.

The displacement measured by the TMR sensor was used to control the amount of pitch shifting produced by a bend based on the pitch estimates. Sensor readings are first processed by a first-order lowpass filter at 20Hz to remove noise and fast transients that are not associated with string bends. After that, a threshold value around the zero-bend DC offset is used to detect the bend direction (upwards/downwards) from the resting position of the string and the estimated displacement mapped to the corresponding range of frequency shift range (see section 3.2). Although a frequency-dependent piece-wise mapping could be more accurate, we employed the mapping obtained for one fret (7th) and used that range as a baseline for the rest.

Using the pitch prediction from YIN and the expected shift amount extracted from the sensor mapping we were able to establish a target frequency for altering the pitch of our instrument.

A time-domain PSOLA (Pitch Synchronous Overlap and Add) algorithm adapted from [24] was then used to manipulate pitch based on this target. By adding a controllable scaling factor to the target shift amount estimated from the sensor readings, the traditional pitch shifting rules can now be modified: a scaling factor of $(-1)\times$ will exactly cancel the natural pitch shift cause by the bend, while a factor of $2\times$ will exaggerate the effect of bending the string. Furthermore, different rules can be set for upwards and downwards bends to disambiguate bend gestures: we could for example, use a negative scaling factor of $(-2)\times$ exclusively for downward bends, effectively inverting the pitch shifting rule and allowing the player to execute downward pitch shifts via this gesture instead. This approach, when combined with a hexaphonic pickup could be expanded to different strings, setting different behaviours per string or even frequency range.

Although this is just a simple example that showcases the possibilities of this technology for augmentation, many other creative uses can be derived from the idea of gestural disambiguation that builds upon the available gestural dictionary of guitar players to extend the possibilities of the instrument.

5 CONCLUSIONS

In this work we have presented a new approach to the acquisition of musical gestures associated with guitar playing based on Tunneling Magnetoresistance (TMR) sensing. Our setup uses tracking of the horizontal displacement of the strings of the guitar (perpendicular to their longitudinal axis) to capture gestures related to left- and right-hand techniques. We demonstrate a characterisation procedure that uses pitch contour estimates to map the sensed displacement to pitch shifts so that the acquired signals can be directly used to estimate pitch produced by string bending in real time.

Moreover, we show how different gestures that are ambiguous with respect to their sonic output can be analysed and differentiated by contrasting features extracted from the produced audio signals with information derived from the sensors following simple heuristic methodologies. We further demonstrate applications for enhanced transcription of string bends and plucked onsets and for designing instrument augmentations that build upon the player's expertise. The proposed sensor technology offers real-time tracking of performance parameters and can potentially be retrofitted on existing instruments without getting in the way of the performer.

Although the sensor setup presents some trade-off between position and monotonicity and would require characterisation for each string and fret, it shows potential for capturing expressive performance parameters in a hexaphonic manner. Future studies will evaluate this aspect taking into account the effects of string cross-talk and analysis of more complex gestures.

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