Separating sound from source: sonic transformation of the violin through electrodynamic pickups and acoustic actuation

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ABSTRACT

When designing an augmented acoustic instrument, it is often of interest to retain an instrument's sound quality and nuanced response while leveraging the richness of digital synthesis. Digital audio has traditionally been generated through speakers, separating sound generation from the instrument itself, or by adding an actuator within the instrument's resonating body, imparting new sounds along with the original. We offer a third option, isolating the playing interface from the actuated resonating body, allowing us to rewrite the relationship between performance action and sound result while retaining the general form and feel of the acoustic instrument. We present a hybrid acoustic-electronic violin based on a stick-body electric violin and an electrodynamic polyphonic pick-up capturing individual string displacements. A conventional violin body acts as the resonator, actuated using digitally altered audio of the string inputs. By attaching the electric violin above the body with acoustic isolation, we retain the physical playing experience of a normal violin along with some of the acoustic filtering and radiation of a traditional build. We propose the use of the hybrid instrument with digitally automated pitch and tone correction to make an easy violin for use as a potential motivational tool for beginning violinists.

Author Keywords

violin, augmented instrument, active acoustics, actuated musical instruments, learning technology

CCS Concepts

•**Applied computing** → **Sound and music computing;** Performing arts; •**Information systems** → *Music retrieval;*

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1. INTRODUCTION

Two common motivations for designing augmented instruments are to extend the sonic capabilities of an existing instrument, or to repurpose the player's existing skill and technique on a traditional instrument. In contrast to traditional acoustic instruments, where sound production is inherently tied to physical construction and energy input from the player, it is common with developing digital or augmented instruments to segment the design into separable modules: interface, processing, sound output.

Most commonly, processing is done on a computer with sound then output to a speaker or public address system, physically separating the sonic output of the instrument from the interface. Separating the two not only alters an instrument's directionality and sonic presence, but also results in the loss of immediacy and subtle haptic feedback many performers rely on [22].

Actuated musical instruments are those instruments artificially excited to create new timbres and sounds [22]. On string instruments, magnetic actuation of the strings is commonly used to create new sounds and means of control. Examples include the commercially available Sustainiac [12] and Vo-96[1], Berdahl's Feedback Resonance Guitar [22, 3] and McPherson's magnetic resonator piano [17].

Another subset of actuated musical instruments are those using active acoustics with structure-borne sound drivers inducing vibration into a resonating body [16]. Active acoustics can be used to alter and control normal acoustic behaviours, exciting specific modes to modify timbre, or counter naturally occurring phenomena like cello wolf tones [20]. IRCAM's *Smart Instruments* project focuses on active instrument control in a variety of instruments including bowed strings [1], metallophones [4], and woodwinds [19].

Active acoustics can also be used to add a wide range of standard audio effects to an otherwise acoustic instrument. This approach is particularly popular for guitars with commercial examples such as the Tonewood Amp[2], Tonik[3], and Yamaha's Transacoustic Guitar[4]. Lähdeoja discusses build-

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[1] https://www.kickstarter.com/projects/38513516/the-vo-96-acoustic-synthesizer

[2] https://www.tonewoodamp.com/ (accessed: 20.1.2019)

[3] https://toniksound.com/ (accessed: 20.1.2019)

[4] https://usa.yamaha.com/products/musical_instruments/

Figure 1: Assembled *svampolin* with foam separating the stick-violin from the resonating body which is attached upside-down, with the actuator beneath.

ing active acoustic guitars in [16, 15]. The Chameleon Guitar by Zoran et al. [30] takes the inverse approach, sensing and modelling acoustic soundboards but retaining external speakers for the final sound.

Active acoustic instruments benefit from retaining a familiar sound and feel, but a significant drawback is that they are additive: the sound of the acoustic instrument is retained. This limits any transformation that seeks to retain the technique and feel of a traditional instrument but alter its original sound.

This paper presents an alternative hybrid acoustic-electronic approach similar to active acoustics, but where the physical inputs of the instrument are acoustically separated from the resonating body. Overholt's Overtone Fiddle [21] demonstrates normal violin actuation exciting a separated carbon-fibre acoustic body hung beneath. Similar to more recent revisions of Lähdeoja's guitar [10], we take Overholt's design a step closer to an active acoustic violin, using a traditional violin body as resonating chamber. Note that if there is no goal of restoring acoustic sound characteristics, one could simply attach small loudspeakers to an electric violin, as seen in [23] or the Fusion guitar[5].

We have built a new violin which we informally call the *svampolin* designed to maintain similar sound and feel to the traditional violin, but with the capability of sonic substitution. In this paper we will present: the svampolin's physical build; a custom-designed electrodynamic pickup capturing the velocity of each string with minimal cross-talk or body coloration; and the actuation of the physical violin body.

We then present an example application of the svampolin as a simplified violin for beginners, where we use automated real-time pitch correction to improve player intonation and real-time bowed-string feature extraction to regulate the timbre. The resulting instrument retains a similar response to the player as an acoustic violin, and use of a traditional violin body as resonator restores many of the acoustic sound characteristics, making it viable as a potential motivational tool in violin learning.

2. INSTRUMENT DESIGN

The svampolin (Figures 1 and 2) comprises an electric "stick" violin with a custom pick-up, an acoustic violin body with no strings, a vibration actuator, an embedded computer, and foam and string to clamp the two violins together.

Figure 2: Component parts of the hybrid violin; the stick-violin with mounted pick-up system is on top with foam, Bela, actuator, and power amplifier in the middle, and the violin body at bottom.

The stick violin is made by Slawomir Ganiec[6]. It provides the fingerboard, bridge and strings to support the core playing interactions[7], while the actuated acoustic body (with no fingerboard or bridge attached) provides the sonic output.

2.1 Electrodynamic Pickup

Our instrument features a pickup whose design is based on the *StringAmp*^{TM} system by Michael Edinger of MusikLab Denmark.[8] The principle of operation is electrodynamic, where according to Faraday's Law a wire moving in a magnetic field leads to an induced voltage proportional to the velocity and the strength of the magnetic field. However, rather than the traditional arrangement used in electric guitars, where the string modulates the magnetic field which is then picked up by a stationery coil of wire, in our arrangement the *string itself* acts as the wire carrying the induced voltage. All strings are grounded at the scroll end, and the voltage on each string at the tailpiece is passed into a low-noise preamplifier described in the next section.

To provide the ambient magnetic field, neodymium magnets are placed underneath each string near the bridge (Figure 3). We found it convenient to place them close to the bridge, where they could be installed on a laser-cut platform without permanent modification to the violin. Since the signal level is proportional to the magnetic field strength, the magnets should be placed as close to the strings as possible, making placement near the bridge more convenient as the string will have a smaller range of vertical displacement due to bow pressure.

This pickup arrangement has several advantages. First, the signal captures the motion of the string in the horizon-

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guitars_basses/ac_guitars/ta_series/ (accessed: 20.1.2019)

[5] https://fusionguitars.com/ (accessed: 27.1.2019)

[6] http://www.urbgan.cba.pl (accessed: 27.1.2019)

[7] The pictured violin is a five string violin, however the presence of a fifth string is not core to the implementation, and any stick-violin would suffice.

[8] http://www.stringamp.com (accessed: 20.1.2019)

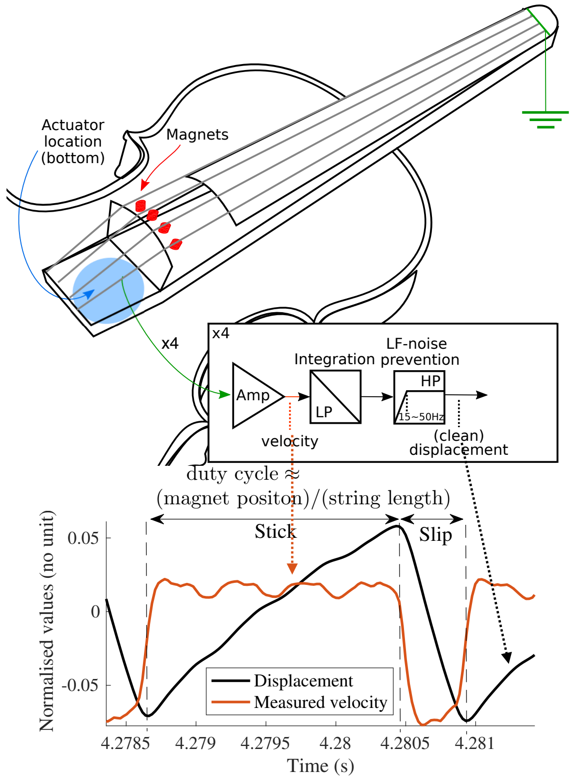

Figure 3: Schematic diagram of the violin and its pickup system using magnets, along with an example of a picked up signal.

tal plane, the same plane as the stick-slip motion of bowing. Second, since field strength is approximately constant for small movements, the signal is a clean representation of string velocity at the point along its length where the magnet is placed, with minimal contribution from bridge and body resonances. This allows the application of analytical models derived from bowed string physics, described further in Section 3. Third, the design can easily be made polyphonic, with a separate signal for each string and minimal crosstalk.

2.2 Preamplifier

For the pickup to work effectively, each string must be conductive along the full length, which is true of many but not all violin strings. The combination of extremely low source impedance and low signal level (no more than a few millivolts full-scale) presents a noise-floor challenge for any preamplifier. Our design, which is shown in Figure 4, differs significantly from the original StringAmp preamp in architecture and purpose. Where StringAmp is a single-channel preamp targeted at producing the highest possible sound quality for live amplification, our application instead calls for a linear polyphonic transducer for real-time digital signal processing. Our design is based on the OPA1612 op-amp which features extremely low voltage noise density of $1.1\text{nV}/\sqrt{\text{Hz}}$. R1 and R2 are thin film resistors, with the smaller than usual 3.3Ω value of R1 minimising the Johnson (thermal) noise in the feedback path. The low source impedance of the string means that Johnson noise is negligible in the source signal itself.

In Figure 4, the gain is set by $1 + \text{R2}/\text{R1} \approx 304$, with C1 providing a high-frequency rolloff, and a further second-order lowpass filter following in the second stage with a corner frequency of $1/(2\pi\text{R3C3}) \approx 21.9\text{kHz}$. A bipolar power supply is required for the first stage. C2 and R5 allow the second stage to be referenced to an offset voltage V_{com}, which in our application is set to 2V to centre the signal within the input range of an analog-to-digital converter.

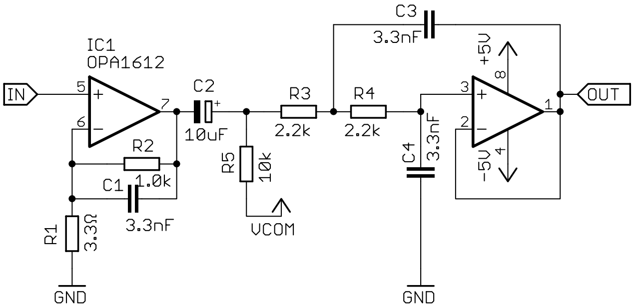

Figure 4: Low-noise preamplifier schematic for electrodynamic string pickups (one per string).

2.3 Digital Processing

The output of each string is processed using a Bela Mini [18] embedded computer, which enables real-time signal processing with submillisecond latencies, meaning that the only meaningful latency arises from the DSP algorithms themselves. Each signal is sampled at 44.1kHz with 16-bit resolution. The Bela Mini is physically installed between the stick-violin and the acoustic body. It is currently powered through an off-board battery.

2.4 Actuation

A 30W Tectonic TEAX32C30 vibration transducer is installed on the acoustic body with specialised adhesive. The choice and placement of actuator was determined empirically based on sound quality, and our choice follows the recommendation of Lähdeoja [15].

We tried actuating a violin with and without sound post and found that having no sound post resulted in better vibration transference. Similarly, we tested different locations on the top and bottom of the violin, including over the bass bar, and decided to place the actuator roughly where a sound post might be. We opted to attach the violin body upside-down so that the violin's f-holes point toward the floor. We did this for two reasons: we felt yielded it better sound radiation, and pointing upward at volumes audible to an audience became prohibitively loud for the player.

For practical reasons, our current instrument mounts the transducer outside of the violin body. Guitars have the benefit that the sound hole is large enough to reach inside to mount an actuator, but installing an actuator within the violin requires removing and regluing the top. We intend to revisit this possibility at a later stage. We will also explore the use of more than one actuator. Lähdeoja [15] discusses how using two actuators on different planes yielded the best perceptual frequency response and most natural radiation characteristics within an active acoustic guitar.

The actuator is currently powered by a TPA3118 30W class-D audio amplifier (using an inexpensive commercial breakout board). This amplifier produces sufficient volume but we find it to be noisy and failure-prone, and it requires an off-board 24V power supply.

2.5 Assembly and isolation

The stick-violin and acoustic body are held together with straps and adhesive, with a thick foam between them for sound isolation. We found this relatively simple approach to be sufficient, though we also considered various vibration-dampening caulks. Isolation was assessed by placing a pickup on the acoustic body with no actuator. We found that the vibration of the strings on the electric violin produced only small vibrations in the body (though the strings also couple to the air directly, making a quiet but audible sound which is readily masked by the actuation if driven at appropriate volume). Similarly, vibrations from the actuator do not couple strongly to the strings, meaning that feedback is not a problem in the applications we have tested.

Future directions can include other types of foam with improved damping characteristics, or ideally, a design where the acoustic body is entirely suspended from the stick-body using tensioned cables.

3. APPLICATIONS

By retaining playing technique and physical familiarity, the svampolin's decoupling of interaction and sound opens up a wealth of extended performance opportunities through audio effects or novel synthesis techniques. One of our own primary motivations was to investigate technological intervention in instrument learning, in particular, the idea of *complexity management*: the transient simplification of an eventually complex instrument in order to optimize the learning rewards cycle [26].

Successful fluency and expertise on an instrument requires sustained practice, which in turn requires motivation. As Kohut writes:

> ...most people, regardless of training, can differentiate between extremely poor and good performance.... This can be, and often is, a negative factor in terms of motivation for continued practice after the first two or three months of study. Good students in particular become frustrated if the tonal results they achieve are poor. But once tone and intonation improve sufficiently, practice comes easier, because it is more fun when one sounds better. [14, p.9]

Though a few months of incompetence might be tolerable for a teenager learning a popular wind instrument, for a challenging new instrument with unknown capacity for virtuosity or an existing instrument that requires longer study to master basic tone production, the patience to continue practicing without musical reward may be too much.

With both basic tone and intonation requiring concerted attention at first, the violin requires intensive long-term commitment prior to musical success. Further, unlike the piano, where a melody can be played on one hand, the violin requires bimanual skill for even the most rudimentary musical result. As Tasmin Little stated[9], "...you can be doing everything right on the violin, but as 90% of tonal production comes from the bow, as long as your bow isn't working, nothing is going to work."

The svampolin was designed partly to study whether artificially simplifying intonation or tone (or both) provides beginning learners sufficient musical reward to improve their motivation to practice. A related question is whether simplifying the violin results in incorrect learning that disadvantages the player when the simplifications are removed (i.e. guidance effects [8]). For instance, a key part of learning is understanding the link between action and sound. Artificially correcting intonation may lead the player to sound better but also inhibit the ability to hear and correct errors, with consequences for later performance on an acoustic violin.

In [24], we explored the effects of full and partial pitch correction on expert and beginner intonation using violin augmentation techniques presented in [25]. In those experiments we used headphones for pitch-corrected audio. However, headphones had drawbacks in bulkiness and suppression of sound from the room. The svampolin offers improvements in these respects.

We currently have two applications, one altering intonation, and the other tone quality.

3.1 Easier violin through pitch correction

With intonation, it is easy to both define error[10] and then correct it. Based on software described in depth in [24, p.181-186], we created an equal-temperament always-in-tune violin. Polyphonic correction is achieved by correcting each string separately. First, in order to remove noise from the current hardware design, input signals from each string are filtered above 4kHz and below 100Hz using 2nd-order filters.

Next, we use a real-time optimized version of Yin [7] for pitch detection and a modified version of Tom Baran's Autotalent[11], which uses a time-domain based pitch synchronous overlap-add algorithm, for pitch correction.

As Bela only has sufficient processing power to pitch correct three strings, while we always correct the A and D strings, correction of the G and E strings is based on which of the two strings is higher volume. Pitch corrected signals are then mixed together for driving the actuator.

In order to accurately detect pitch with sub-12ms latency, we previously used a physical sensor to capture finger placement on the fingerboard [25], however using the electrodynamic pick-up presented earlier, string signals are clean enough that (although we have not numerically evaluated its performance) we find qualitatively that audio-only pitch correction at low latency still produces nearly error-free results. Audible errors are almost exclusively restricted to the early transients and final decay of a note.

Moreover, though we can program the svampolin to snap strictly to the nearest semitone, we can also correct intonation only partially, allowing some heard intonation error, or even exaggerate intonation error to highlight mistakes.

3.2 Easier violin through tone regulation

Unlike equal-temperament intonation, identifying good tone and correspondingly how to correct poor tone within an audio signal is not as straightforward. However, it is possible to rectify the tone quality to a certain degree in that we can define a signal model for the desired tone, and then enforce a measured violin signal to be coherent with that target signal model.

3.2.1 General technique

To define the desired signal model, it is necessary to examine how bowed string vibrations operate. Helmholtz observed that the bowed string vibrates in a lateral triangular shape, with the corner of the triangular travelling up and down between the nut and the bridge. Each time when the corner passes under the bow, the interaction between the bow and the string switches between a sticking and a slipping state

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[9] Violin or Guitar: Which is Easier? Originally broadcast on 16 Sept 2014 for BBC Radio 4 Today show with guitarist John Etheridge.

[10] Intonation error is easily defined within the context of equal-temperament. Expert violinists regularly use other tuning systems or deviate from equal-temperament for expressive reasons, but for a beginner, we consider it reasonable to base intonation on equal-temperament.

[11] http://tombaran.info/autotalent.html (accessed: 20.1.2019)

[28]. Raman [27] later theorized that, making the assumption that the string displacement is lossless and the string is ultimately flexible, the measured string displacement indeed gives a triangular signal, whose *duty cycle*, defined as the ratio between the lengths of the positive and negative slopes within the period, corresponds to the relative measurement position along the string [29] (as illustrated in Figure 3[12]) and can be modeled as such.

In practice the interplay of string losses and stiffness, complex bow-string interaction characteristics, and the feedback of the violin body to the string cause deviations from the straightforward triangular model, e.g. the duty cycle can change, the corners of the signal become rounded [6] and some particular phenomena such as *multiple flybacks*, *multiple slipping* or *raucous motions* can occur [11].

The simplicity of the string motion signals inspired us to design a time-domain algorithm that approximates the original signal with straight line segments (separated by *break-points*), to enable the extraction of precise and unambiguous tone quality features. A first implementation of such an algorithm was designed in earlier work [5]. In that algorithm, initial break-point locations are detected with a simple RMS-threshold technique (which is reasonably accurate given the pertinent displacement signal shape). Next, the break-point locations are optimized by minimizing the error between the linear segmented model and the data, using an iterative regression method. This implementation enables the precise and real-time estimation of the fundamental frequency, amplitude and duty cycle of the string's displacement signal.

Recently, the algorithm has been extended to include an estimation of the corner rounding, enabling a more accurate and precise analysis of the tone quality. The previous algorithm could be adapted to perform a segmented regression of the velocity signal. As the rounded displacement corners can be approximated by parabolas, the velocity signal can be modelled as a sloped straight line, alternated by the zero-slope segments corresponding to the stick and slip states of the bow-string interaction, which results in a *trapezoidal* velocity signal model. Hence, the computational task remains a linear segmented regression, with added zero-slope constraints, which provides an unambiguous model that is implementable with the same mathematical approach requiring minimal code adaptation.

Figure 5 shows an example of a captured velocity signal and a resulting segmentation.

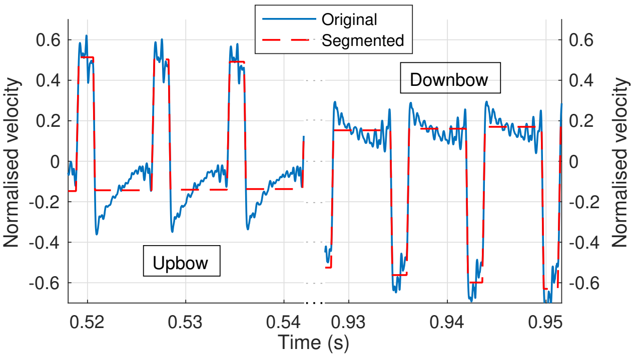

Figure 5: Measured string velocity signals and segmented approximations. Left: upbow, right: downbow.

3.2.2 Discussion

We have carried out initial tests with both an expert and beginning violin player and observed how indeed, notes played to a classically correct standard abide well to the trapezoidal velocity signal model, while notes played with poor playing technique resulted in many tone quality perturbations that deviate from the model. Many (small) perturbations, typically occurring in the vicinity of a good playing style, do not significantly alter the linearly segmented approximation. Hence, they can be simply erased by enforcing the model, resulting in a what could be considered corrected tone quality. However, remaining work requires including perturbations currently excluded from the model that still influence the model parameters. For instance, raucous tones tend to produce chaotically fluctuating parameters, which could be corrected by filtering the parameters when sustained oscillation regimes are detected.

Both automatically correcting intonation error, and forcing string signals to adhere to an idealized physical model are performed with the intent to make basic sound production easier for a beginner. However these are artificial disruptions of normal violin behaviors which may be unsettling for highly-practiced performers, something we have already seen in our study looking at the experts' experience of pitch correction [24, pp. 192-241]. Further, our simplifications come at the cost of limiting expressivity, though there is reason to believe this trade-off is beneficial when matched to user skill [13].

4. CONCLUSIONS

Any of the components in Section 2 can be used independently. The pickup system in particular offers an easily-implemented high-performance approach to per-string sensing on any instrument with conductive strings, whether or not the strings are ferromagnetic. Below we comment on some of the possibilities for combining sensing and actuation.

4.1 Substitution, not Addition

The benefits of collocated interaction and sound production are well-established [22]. The most common approach to collocated string instrument augmentation is to start with an instrument with a direct mechanical action-to-sound coupling, then add further sonic layers through actuating the strings [3, 17], soundboard [16, 2] or resonant cavity [9]. The starting point could be an existing specimen of instrument or a purpose-built acoustic system as in Úlfarsson's *Halldorophone* [9] or Overholt's *Overtone Fiddle* [21]. In any of these cases, the direct acoustic coupling from action to sound hinders sonic transformations where the original sound is not helpful, such as pitch shifting, attenuation or timbre changes that are not purely additive.

Further, our motivational target is to help beginners learn violin and implicit in that is the end goal that they be able to play an unaugmented violin. To work, both pedagogically and motivationally, players need to feel like they are playing a real violin. This rules out a violin interface linked to speakers and clearly, if an active acoustic violin was producing audible acoustic sound along with the corrected audio, it would be highly disruptive. Hence a hybrid actuated violin is the only viable option.

Our approach mostly avoids the obstacle of direct acoustic sound. Any electric violin will produce some audible sound via direct string-to-air or string-to-bow-hair coupling, but this can be largely masked by an actuated sound of ordinary volume. However, an important consideration in the substitution approach is to maintain the subtlety of in-

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[12] Note that the (near) coincidence of stick-slip sections and up-down slopes is because bowing occurred close to the pickup location.

teraction of the original instrument, which no longer flows automatically from the acoustic coupling, but instead must be supported by the digital signal processing system. High sampling bandwidth and low latency are important conditions, and ideally, any DSP system should have a robust, predictable response that supports the sensorimotor training of the player.

4.2 Future Design Directions

The svampolin shares many similarities with the familiar acoustic violin. Its sound shares certain characteristics but is not identical. Apart from the five-string stick violin, two other notable differences are its extra weight and the fact that the strings are elevated with respect to the chin rest. We do not find the added weight to be a problem, though future redesigns should either lower the strings or raise the chin rest. Other practical improvements could include unified on-board power for the processor and amplifiers, eliminating all need for cables, and a robust physical assembly that travels more easily and can fit in a regular violin case, with or without some modular assembly.

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