The EV: An Iterative Journey in Digital-Acoustic String Instrument Augmentation

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Abstract

Numerous experiments in bowed string augmentation have been undertaken, with each reflecting the values and interests of the builder. The EV takes a unique approach, with the convolution of a synthesized and acoustic string signal at the foundation of its design. Through an iterative hardware and software development process, three versions of the instrument have been created, each building toward the goal of a robust compositional and performative platform for exploring the shared boundary of electronic and acoustic sound. Spatialization and physical modeling algorithms have furthered the instrument's engagement with the interaction between physical and virtual acoustics. This paper examines the iterative design process behind the instrument and its relationship between digital augmentation and acoustic resonance.

Keywords

chordophone, string controller, convolution, cross-synthesis, augmented stringed instrument

1 Background

Over the past 50 years, the bowed string interface has remained a rich site of exploration for instrument builders. Seeking to expand its expressive potential within the context of electro-acoustic music, each experiment has grappled with the challenge of adapting these instruments to electronic and digital frameworks. Their pitch is not identified as easily as that of a keyboard and the amplitude of the four strings is harder to track than that of monophonic instruments. Despite resistance to straightforward digital integration, the violin family's central role within Western classical music and its expressive potential have sustained ongoing experimentation. Rather than discouraging innovation, these complexities have sparked waves of creative responses, each navigating the tensions between acoustic traditions and digital augmentation in diverse ways.

Some approaches aimed to enhance or augment the instrument's natural resonances. Max Mathews's Electronic Violin incorporated electronic resonators to emulate the reverberance of an acoustic violin's body [16]. While this method sought to preserve the instrument's traditional sound within an electronic medium, other approaches have explored ways of extending its sonic potential beyond acoustic precedent. Actuated instruments, such as the Halldorophone [30], use transducers both on the strings and within the acoustic body to extend resonance through the creation and control of feedback loops.

Other experiments use the violin as a controller, extracting only pitch and amplitude information. The VSC-1, a prototype of the Zeta, used conductive sensors to track finger position with the goal of controlling synthesizers [19] [17]. Eventually, the Zeta abandoned this approach in favor of pitch tracking the acoustic string [29]. Other experiments explored hardware-assisted pitch tracking, in which the physical location of the depressed string was reported to the software, improving detection accuracy [22]. Rather than using pitch information to control a synthesizer, the Svampolin built upon this prior work to correct pitch and timbral inconsistencies, outputting the result through an actuator on the instrument's body [21].

Abandoning the traditional violin form entirely, the BoSSA (Bowed-Sensor-Speaker-Array) is a "deconstructed violin" that separates the instrument into its primary physical interfaces [27]. Forgoing acoustic strings, its fingerboard houses a single linear position sensor which tracks finger position; the bow rubs against four force-sensing sponges, driving synthesis algorithms. Departing the physical realm, Coretet is a virtualized string quartet that uses Oculus Touch controllers [6] as an interface. Players interact in a shared virtual space via headsets, while hearing each other's instruments (which are synthesized with physical models).

Some instruments extend the conventional functionality of the violin with arrays of onboard sensors. Built on an electric upright bass, the SBass is extended with additional pickups, buttons, and even a mouse trackpad, which control processing on a laptop [1]. The Overtone Violin was designed to push "the cutting edge of musical performance... and [maximize] human physical/cognitive skills in the control of digital multimedia systems" [20]. Equipped with a range of sensors, it aimed to "put real-time signal processing under direct expressive control of the performer, thereby pushing the envelope of violin performance and composition into completely new areas" [20].

Two questions have persisted within augmented string experiments: Is the physical string retained (or replaced with a sensor)? And if retained, what role does it play in sound generation? In the Electronic Violin, the string functioned as an acoustic element, with Mathews's innovation lying in the recreation of the violin body using electronic resonators. The Zeta, by contrast, used the string as a source of pitch and amplitude data. In many actuated instruments, the string serves both as a melodic component and as the exciter or agent within a feedback loop.

Embracing the traditional bowed string mechanism, the EV (short for electronic viola or violin) explores the boundary between the acoustic and electronic through cross-synthesis. Its

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pickups capture the acoustic sound for two uses: to extract pitch and amplitude data, driving a synthesizer, and to convolve the acoustic signal with the synthesized output. The result is a sound that embodies the physicality of the string while extending it into the imaginative space of computer-generated audio. In the EV, the string's vibration becomes the nexus of the player's intention—just as the voice of a singer conveys their emotive expression. Jean-Claude Risset described synthesized sound as evocative of a virtual world: immaterial yet perceptually real, capable of suggesting alternate realities rooted in perception rather than physical environment [24]. Seeking to unite the nuanced expressivity of the acoustic string with the expansive sonic palette Risset describes, the EV uses FFT convolution algorithms to fuse these two realms.

Eschewing additional control modalities, the instrument's ontology centers on shaping electronic sound using the traditional techniques of a trained acoustic string player. As the instrument has evolved, this foundational premise—the juxtaposition of acoustic and electronic sound—has expanded to include immersive virtual spaces and physical modeling.

2 Objectives

The EV's design has been shaped by two interrelated objectives: capturing the idiomatic nuances of string playing for the creation of electronic music, and retaining the expressive power of embodied string performance.

2.1 An Interface that Captures the Nuance of String Playing

Sensors used to translate physical movement into control data are often reductive and limited in dimensionality. While their ease of implementation is a clear advantage, they can fall short, especially when compared to the storied precedents in instrument design over past centuries and across diverse cultures. Even with the advent of advanced sensors, interfaces tend to gravitate toward simpler arrangements of buttons and knobs. For example, the absence of string-like controllers pales in comparison to the ubiquity of keyboard-based interfaces. While there are multiple explanations for this, Ryan Didick points to a "claviocentricism" in Western music, where the centrality of the keyboard has fostered an embedded "historical standardization" and "cultural logic" [4]. Numerous instances are evident throughout digital music frameworks, from MIDI to DAW design. The keyboard was termed "dictatorial" by Buchla, and distracted from the "knobs and the wires and the interconnections and the timbres" [26]. Wessel and Wright questioned the electronic music industry's "insistence on standard keyboard controllers" [28], and technologist Jaron Lanier laments that MIDI can only represent "the tile mosaic world of the keyboardist, not the watercolor world of the violin" [8]. While this standardization has been beneficial in many ways, its limitations become especially apparent when attempting to interface with computer music systems at the level of dimensionality that non-keyboard instrumentalists are accustomed to. In contrast, the EV aims to capture the full spectrum of sonic nuance articulated by the performer.

The bow shapes sound based on various factors: placement relative to the bridge, drawing speed (which can also affect pitch), and arm pressure. Additional considerations include the bow's angle and its tilt relative to the string.

The left hand also plays a significant role. Beyond determining pitch, the pressure (or lack thereof) applied to the string and the part of the finger used (the tip versus the fleshy pad) affect both timbre and the string's ability to vibrate. The coordinated actions of the bow and left hand can produce less obvious effects as well. For example, simultaneously releasing both bow and finger pressure causes a more pronounced decay, as the reduced finger pressure dampens the ringing of the strings.

Through the use of a phase vocoder, these sonic nuances become embedded as information within spectral analysis. While there are many potential applications of this data, the EV focuses on the convolution of the instrument's acoustic signal with that of a synthesizer, tracking pitch and amplitude. The electronic music palette is vast, and its possibilities are compelling for music creation. Similarly, the expressive potential of bowed string instruments is also vast, and equally compelling in performance. The EV strives to integrate the strengths of these two practices into a complementary whole.

2.2 The Power of Embodied String Performance

While the computer can generate limitless sonic possibilities, this very strength can also present a challenge in performance. Before the advent of electronic and digital platforms, sound creation relied on kinetic input, with the sonic result typically corresponding to its intensity. Wessel noted that "we hear in accord with hypotheses that we have about the world" [2]. This suggests that our musical experience is intertwined with our experience of the world. Marc Leman explores this connection, asserting that both listening to and creating music are "constrained by body movements, which play a central role in all musical activities. The embodied music cognition approach posits that the (musical) mind results from this embodied interaction with music" [10].

While many forms of electronic music performance have physical aspects (even pushing 'play' for a tape piece), the EV's objective is to not only preserve the embodied creation of sound but also to retain the kinetic dynamic of the bow's force against a physical string. In live string performance, this relationship—fully expressed—can create a powerful experience. The somatic connection between listener and performer, as described by Leman, is further appreciated through the dynamic between the performer and the instrument's acoustic result. Preserving this interaction as the foundation for electronic sound generation is a central aim of the EV.

3 The EV's Genesis and Overarching Design Concerns

The EV has undergone three iterations: EV 1, EV 2, and EV 2.5. Design efforts have centered on sensors (for pitch and amplitude tracking), the instrument's body, and software. Throughout these iterations, musical output has remained a central focus.

Software design has primarily been within Pure Data (PD), accompanied by additional C++ code. Body specifications have prioritized securely housing the sensors, structural integrity, and ease of play, while retaining the standard dimensions of a 16-inch viola.

4 EV 1

EV 1 served as the initial foray into the project, a step into the unknown before a larger trajectory had been fully considered. A retrofitted acoustic viola, shown in figure 1, was chosen as an accessible point of entry.

Figure 1: EV 1 with two processing boxes and its initial pickup.

4.1 Sensors

As earlier pitch-tracking experiments using *fiddle~* proved undesirable due to latency and accuracy issues, the decision was made to embed conductive sensors under each string to track finger position (similar to [9]). A current would travel through the strings and, when depressed, would pass to the conductive fingerboard. Functioning as a voltage divider, the voltage output from the sensor could be mapped to a corresponding frequency.

Drawing on the use of graphite as a resistive material in potentiometers, a mixture of methylene chloride, graphite powder, and thermoplastic beads was created to form the sensor. A groove was cut in the fingerboard under each string, and the material was packed into the cavity in layers. Once dried, it was filed down to be flush with the surface of the wood. Contacts were installed at both ends of each resistive strip, with a conduit cut into the neck to house five wires: one for each string and another for ground. Power was supplied at the other end of the fingerboard. To improve contact between the strings and the fingerboard, the A and D strings were replaced with a second set of G and C strings, pitched up a step. In software, these strings were re-pitched to their original octave, but when processed through the FFT convolution, they resulted in a darker timbre.

To enable independent amplitude tracking for each string, a quadrophonic pickup was designed. Four bobbins were constructed, each with a cylindrical nickel-alloy magnet core. The resistance of the wire winding was tested during the winding process to ensure consistency across pickups. Once assembled, the four pickups were encased in thermoplastic to improve durability and structural integrity.

Truncated RJ45 (Ethernet) cables were used to connect both the pickup output and the conductive strips to Ethernet couplers fastened to the lower bout of the viola. Longer cables connected to the other side of the couplers were used to carry both signal sets from the instrument to two processing boxes. One box housed a quad preamp and envelope follower circuit of Nic Collins's design [3], and the second box contained pull-down resistors for the pitch strips and an Arduino Mega for analog-to-digital (ADC) conversion. The preamp unit also included four audio outputs, which bypassed the envelope follower.

4.2 Software

An Arduino program [1] was developed to transmit the 10-bit value for each sensor to PD via the *comport* external, yielding a 1 kHz sample rate per sensor. Each sensor sample was split into a 7-bit data byte and a status byte that encoded the upper bits along with a sensor-specific offset, enabling synchronization and recovery in the event of dropped bytes during serial transmission. The fingerboard sensor data was then mapped to corresponding frequencies using a linear interpolation algorithm. The software gradually took shape, informed by the composition process. The signal flow structure adhered to a conventional audio production paradigm: control input, audio generation (synthesis), and mixing (including effect sends).

EV 1 incorporated an FM synthesizer, four FFT algorithms—two from [25], one from [7], and one designed by the author—as well as the *rev1~* reverb object. Additionally, a mixing console was implemented (enabling signal routing between synthesis modules) along with a CV matrix (for applying envelope control to various synthesis parameters).

4.3 Results

4.3.1 Successes. The initial EV 1 iteration proved successful: detailed pitch and amplitude tracking provided a level of control over the synthesizer that felt intimately connected to the sensation of string playing. There were concerns that the 10-bit conversion might not offer sufficient resolution; however, it proved acceptable. Furthermore, the various convolution algorithms produced compelling sonic results, adding the desired nuance to the synthesized sound and occasionally yielding welcome surprises.

[1] https://github.com/brianlindgren/arduinoSensorTransmit

The instrument's latency measured approximately 50 ms, which remained usable for slow to moderate tempi.

EV 1 was used to create two compositions. The first was *Etudes & Vignettes* [11], a work of six short movements, each composed of multi-layered tracks. The use of FFT convolution (section 1) can be heard throughout. In the first movement, the opening D pizzicato triggers an FM synthesizer, which is convolved with the string's acoustic signal. This algorithm (FFT 2), of the author's design, asymmetrically combines the two sounds: only Source B's magnitude and Source A's phase are used. This results in the output's spectral shape and loudness being shaped by Source B, while Source A governs its temporal evolution and harmonic structure, producing a noisy, inharmonic convolution. This can be heard in the strident quality of the opening line. The other two layers are processed similarly, however, the FM synthesizer is sent wet-only to the convolution algorithm, and the pulse-width of the square wave is modulated by the string's amplitude, resulting in an output that is slightly less direct, yet more dynamic than the first layer. In contrast, the second movement makes use of an algorithm by [7]. The FFT data from the synthesizer functions as as a magnitude filter for the string's phase content, giving the string a brighter timbre, like an overblown wind instrument, and also more harmonic than FFT 2.

The second work, *Nuages* [12], adopted a more acousmatic approach, treating EV 1 as a sound source from which short fragments were extracted, transformed, and reassembled into a fixed-media composition. Due to the nature of the composition process, processing parameters were not noted.

4.3.2 Shortcomings. Despite its successes, EV 1 had several shortcomings. While the pitch data obtained via the Arduino remained consistent for an hour or so, it would eventually drift from the string pitch, requiring remapping. In retrospect, this may have resulted from fluctuations in the battery-powered envelope follower, compounded by inconsistencies in the conductive material: the groove dimensions were irregular and the material contained air pockets. Additionally, the analog envelope follower had a limited dynamic range, restricting the instrument's full expressive potential. Loose electrical connections on the instrument's body also became an issue, as the retrofitting lacked proper fastening methods for securing components. A major hindrance was persistent crosstalk between strings. Suspecting sympathetic resonances were being amplified by the instrument's body, insulating foam sealant was applied inside the body, but the issue remained unresolved. Both the successes and the identified shortcomings led to the development of a second iteration, EV 2.

5 EV 2

EV 2 introduced a custom-built 3D-printed body (figure 2) designed to better accommodate sensors and connections, while the adoption of printed circuit boards (PCBs) aimed to mitigate wiring and connection failures.

5.1 Body

A new body was designed using Autodesk Fusion 360, with primary considerations including structural integrity under string tension, optimal sensor housing, and the tactile feel of a traditional instrument. The specifics of 3D printing both forced accommodation in the design and presented opportunities. Due to the flexible nature of polylactic acid (PLA) filament, it was decided that the conduit running through the neck would also house a carbon fiber rod for structural reinforcement. Additionally, the limited size of the printing bed required the instrument to be printed in three separate pieces: fingerboard, body, and chinrest. Dovetail joints were incorporated to securely lock the 3D-printed components together, while the carbon fiber tube and bolts ensured the joint could withstand string tension. As an added benefit, 3D printing allowed for the integration of conduits through the fingerboard and body, providing dedicated pathways for wiring.

Guitar machine tuners were selected for tuning stability and ease of installation. Positioning the tuners near the chinrest shifted the instrument's balance toward the collarbone, making it feel lighter in the left hand compared to a traditional viola. The instrument retained two Ethernet jacks for transmitting pitch and amplitude information to a processing box.

5.2 Sensors

The presence of inter-string crosstalk was a hindrance in EV 1. Suspecting that the oscillation of a string might be transduced by its neighboring pickup, EV 2 employed a custom-built infrared (IR) pickup. An IR LED was positioned 180 degrees opposite an IR photodiode, casting the oscillating shadow of the vibrating string. The same preamplifier design was retained, but the hardware envelope follower was omitted in favor of a software-based solution. This included a slew limiter (restricting upward and downward signal motion over 44 samples), a two-pole lowpass filter at 200 Hz, a highpass filter at 120 Hz, a full-wave rectifier, and a one-pole lowpass filter with an amplitude-derived variable cutoff between 20–120 Hz. Finally, the *threshold~* object was used as a Schmitt trigger.

In an effort to achieve more consistent resistance across the length of the conductive strips, EV 2 used conductive PLA instead of the graphite-thermoplastic mixture. Each strip was printed and inserted into corresponding grooves along the fingerboard.

5.3 Software

Rather than an Arduino, EV 2 employed a Bela single-board computer for digital signal processing. An enhancement, the Bela's ADC supported a higher 16-bit resolution and an analog sampling rate of 22.05 kHz. It also had the capacity to run PD patches independently, without the need for a computer. However, due to the limited number of audio input pins the sensors were routed through the analog inputs, foregoing the benefits of delta-sigma noise reduction. The patch was transferred to the Bela, with the exception of the GUI objects, which remained on the laptop and communicated with the DSP processes on the Bela via Wi-Fi. The patch also required increased processing efficiency on the less-capable Bela; many *switch~* objects were added to reduce unnecessary computational load. Additionally, a throttle was designed to control the GUI update rate; because the Bela's design prioritizes audio processing, excess GUI (network) data can overwhelm the networking functionality.

A second FM synthesizer (based on a different design) and a phase distortion synthesizer were added, along with transfer functions for waveshaping at various points in the signal chain.

5.4 Results

While EV 2 demonstrated clear advancement, new issues emerged and some existing challenges persisted.

5.4.1 Successes. Overall the electrical connections became significantly more reliable. Unlike EV 1, which was deemed too

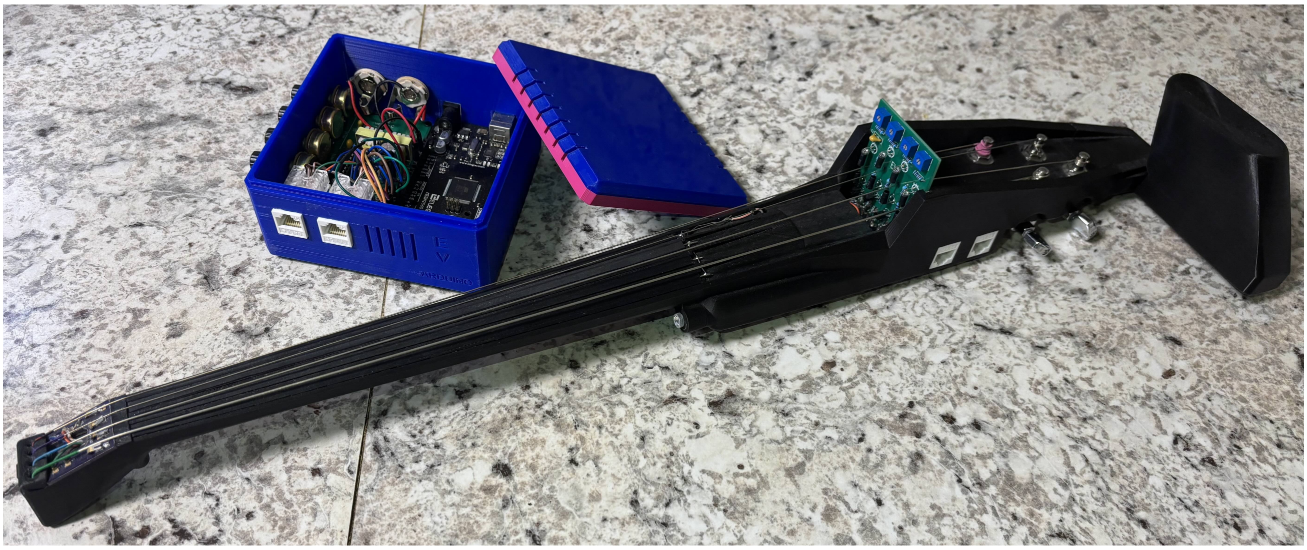

Figure 2: EV 2 with a processing box housing an Arduino and preamplifier.

unstable for stage use, EV 2 was successfully employed in several performances, a major step forward toward creating a robust, stage-worthy instrument. While latency was not formally measured, it was noticeably reduced. The conductive strips also proved more reliable for pitch tracking, likely due to the consistency in resistance, and possibly a more stable power supply.

5.4.2 Shortcomings. Contact between the string and the surface of the strip remained an issue. Although the string could be depressed onto the strip, the electrical contact was not as consistent as it had been with EV 1, perhaps due to the textured 3D-printed surface. Another concern was flex in the neck; as the strings were tightened, the action became slightly higher than anticipated in the design. Furthermore, any change in pressure on the neck would result in a small shift in pitch.

Crosstalk between strings was a persistent problem. Suspecting that light may be scattering into adjacent photodiodes via unintended reflections, heat shrink tubing was added to each transmitter and receiver to act as a blinder. While this did not resolve the problem, it did make the receiver less susceptible to ambient light. Later, a hood was designed for the pickup, enabling outdoor performance in sunlight or under incandescent stage lights.

After transferring the PD patch to the Bela, the sound of the processing changed dramatically. It was discovered that some objects central to the project could not be compiled for use on the Bela. Although this setup was used to compose *Recording 7 Noise* [5] and for live improvised performances, processing was ultimately moved back to the laptop, and the Bela was replaced with the Arduino.

Having taken the first step in designing a custom body for the EV, but still encountering unresolved issues with basic functionality, plans for EV 2.5 quickly came into focus.

6 EV 2.5

Designed as a revision, EV 2.5 (figure 3) aimed to address the shortcomings of EV 2.

6.1 Body

Recognizing that the EV 2's neck lacked sufficient stiffness, EV 2.5 incorporated tough PLA in place of standard PLA. Additionally, a more robust carbon fiber tube support was implemented: a 6 mm diameter tube inserted into an 8 mm tube, resulting in a 4 mm thick wall.

6.2 Sensors

Rather than 3D-printed conductive strips, EV 2.5 used conductive rubber. Recognizing that the contact between the string and the conductive surface was critical, it was hypothesized that the pliability of the rubber could slightly "hug" the string, improving the connection. Strips of 0.5 mm-thick rubber were cut and placed into the grooves of the fingerboard's surface. Electrical contact at the top and bottom of each strip was established using small bolts. Corresponding nuts were inserted into slots within the body's surface; the bolts passed through small holes in the rubber, pressing it against the nut.

Still contending with crosstalk issues, the original Nic Collins preamp design was re-evaluated. It was discovered that the hex inverter was the source of the problem. While the original design is monophonic, the quadrophonic version had impedance mismatches, allowing output from one channel to flow from the summing stage back into the signal path of another. Switching to an op-amp ultimately resolved the issue.

Although the pickup noise had dramatically improved since EV 1, the system's noise floor still prevented reliable tracking of quiet playing. Suspecting an issue with the infrared design, the positions of the transmitter and receiver were changed: rather than the transmitter shining directly into the receiver, both were angled at 60 degrees to each other. In this configuration, the light reaching the receiver was reflected off the string. While measurements were not taken between the two versions, the adjusted placement noticeably reduced the noise floor.

Lastly, the Bela was reintroduced as an ADC due to its higher sample rate and greater bit depth. A C++ program was developed to transmit sensor data via USB using Open Sound Control (OSC) to PD, where a system was implemented to parse the data with

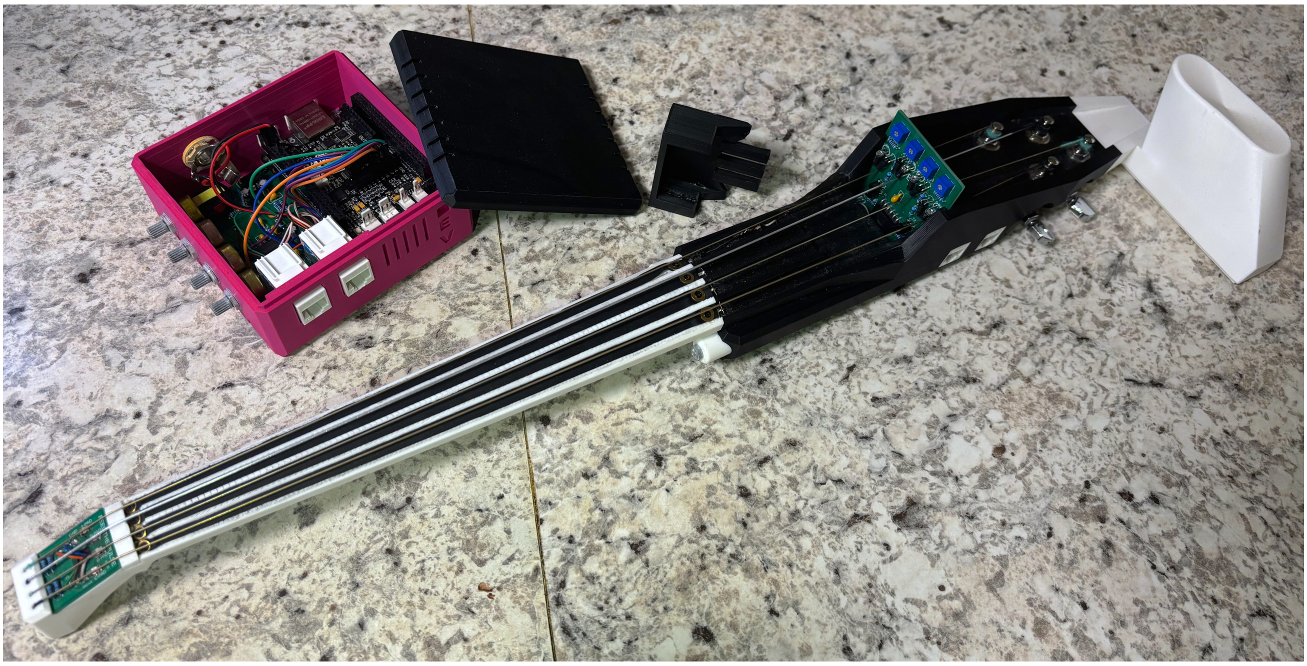

Figure 3: EV 2.5 with a processing box housing a Bela and preamplifier. Also shown is the hood for the IR pickup

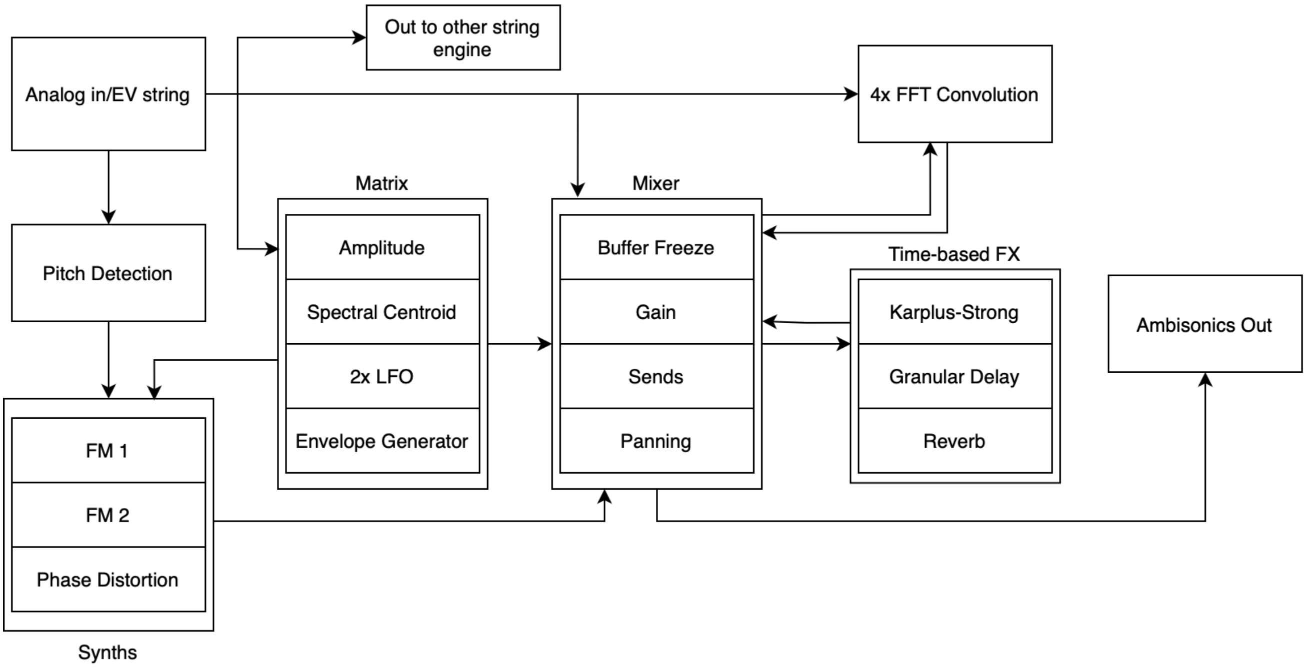

Figure 4: EV's signal flow

minimal latency[2]. A circular buffer writing to the auxiliary OSC process ensured uninterrupted data flow between the Bela and PD, where a corresponding circular buffer (to protect against transmission jitter) received data.

6.3 Software

As the EV achieved greater reliability, efforts were made to expand software capabilities. A preset system was implemented to enable changes in system state. While the instrument had always been polyphonic, most settings were previously global across all strings; with EV 2.5, each string gained independent parameter control. New effects included a grain delay and a buffer freeze (based on a PD PaulStretch implementation [23]), which could be applied independently to each mix channel. The grain delay also included a function that allowed the delay line to cease writing new input and recirculate existing material. As additional software modules were introduced, the number of parameters

[2]https://github.com/brianlindgren/Bela-to-PD-over-OSC

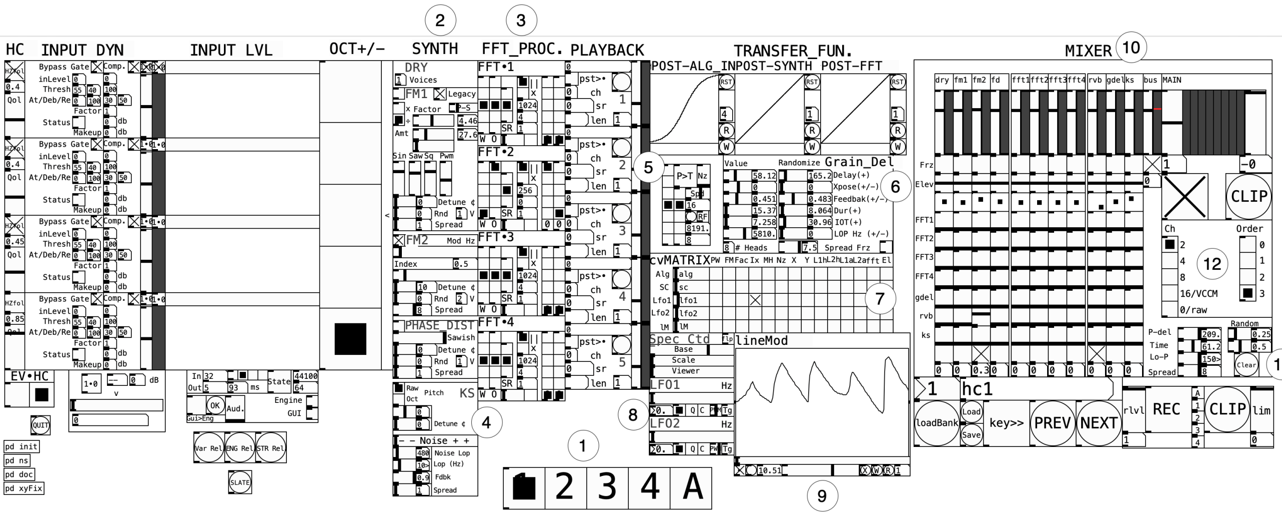

Figure 5: EV's GUI. 1) Current string displayed. 2) The three synthesizers. 3) Four FFT convolution engines, with settings for sample rate, overlap, window size, input swap, and source selection. 4) Karplus-Strong effect. 5) Buffer freeze, with settings for overlap, window size, playback rate, and refresh. 6) Granular delay. 7) CV matrix. 8) LFOs. 9) Envelope generator. 10) Mixer. 11) Reverb. 12) Ambisonics options.

per preset grew accordingly, with each string currently using 396 independent parameters.

The CV matrix was expanded with additional sources, including a spectral centroid tracker, LFOs, and a triggerable custom-drawn envelope, along with corresponding new parameter destinations. A major step forward in spatial control came with the addition of a panning engine for multichannel playback. Initially, a system similar to Vector Base Amplitude Panning was developed, but this was soon replaced by a third-order ambisonic engine, coined *ambiNilla*[3].

A basic physical model, derived from the Karplus–Strong algorithm, was implemented. All sound modules and signal paths were also upgraded to support up to eight multichannel voices, each capable of slight detuning and controlled parameter randomization. Individual voices could be spatially distributed across the soundfield, enabling immersive sonic possibilities.

With the growing processing overhead, the *pd* ~ multicore object was introduced, assigning each string to its own core, while the ambisonic decoder and GUI were allocated separate cores, utilizing six cores in total.

As with previous EV iterations, the mixer retained the ability to route any mix channel's (now multichannel) signal to the input of another module. The newly added modules further expanded the routing possibilities. For example, a synthesizer's output can be sent to a convolution algorithm, processed with reverb, routed to another convolution engine, and then passed through the grain delay before reaching the final output. See figure 4 for a signal flow diagram and figure 5 for an annotated view of the GUI.

6.3.1 Zero Crossing Pitch Tracking. While experimenting with a C++ port of the EV software, a simple zero-crossing pitch detection method was implemented. Its accuracy and responsiveness were impressive, perhaps due to the clarity of the IR pickups (figure 6). Even the 'noise' at the beginning of a pizzicato or bowed note, which caused a fast succession of misreadings, convincingly paralleled the acoustic noise of a transient. The C++ detector was then ported as a PD external called *zDet~*[4].

Unlike the earlier sensor-based finger-tracking approach, this method eliminated the need for a time-consuming calibration process. A significant breakthrough in the EV journey, this resolved the earlier pitch tracking issues, rendering the conductive strips obsolete.

6.4 Results

Perhaps the more significant of the two revisions, EV 2.5 resolved most of the remaining issues present in EV 2, and realized the vision first imagined in EV 1.

Crosstalk was eliminated with the op-amp. Body flexion was improved and no longer affected the action; however, slight flexing remains and will be addressed in future versions. Pitch tracking was stabilized using the zero-crossing detection method. The signal-to-noise ratio (SNR) improved, though with a dynamic range of approximately 60 dB, there remains room for refinement. Lastly, the software capabilities expanded considerably.

The EV was finally able to reliably perform *Etudes & Vignettes* live [13], fulfilling the composition's original vision. Additionally, a new work, *Daughter of the Stars* [15] [14], was composed to take advantage of features introduced in EV 2.5.

String players often consider a room's reverberation as an extension of both the instrument's body and the resonance of the strings. With its new multichannel capabilities, the EV further explored the hybridization of real and virtual space. In *Daughter of the Stars*, the immersive qualities of ambisonics, combined with artificial reverberation, allow the performer to 'play' the virtual space in much the same way that an acoustic environment merges with an instrument's natural resonance. With the signal chain now supporting up to eight voices (section 6.3), the expanded reverberation can more convincingly render an immersive environment, helping to "assimilate the unknown to the familiar," as described by Risset [24].

[3]https://github.com/brianlindgren/ambiNilla

[4]https://github.com/brianlindgren/zDet

Additionally, the inclusion of the grain delay and buffer freeze effect made possible the perpetuation of sound beyond the drawing of the bow, allowing for the decoupling of input and continuous sound, and expanding compositional potential. For example, throughout *Daughter of the Stars*, sound is continually captured and recirculated within the buffer of the grain delay, allowing for the creation of multi-layered sound without fixed media.

A recent development was the adaptation of the EV software as a processing tool for external instruments. Much like classic synthesizers—such as the Korg MS-20—that allow external signals to be routed through their internal signal chains, the EV software was repurposed for use in *experiments from the n-space*, a composition for HYPERCUBE: a quartet of saxophone, guitar, piano, and percussion. The result was compelling: the composition has timbral and aesthetic similarities to the EV, but cast onto a different instrumental framework, merging the quartet's acoustic voices with the EV's processing paradigm.

6.4.1 Latency Measurement. Latency was measured at 27 ms total (figure 6). Performing an acoustic-to-acoustic round-trip latency measurement, a microphone was placed next to the EV string, and another next to the output speaker; a string was then plucked with the software configured to pass the signal unmodified. Recorded in Audacity, the distance between transients was measured. Sources of latency include: the Bela ADC buffer (360 μs) [18], circular buffer (360 μs) (section 6.2), OSC and USB transmission, PD receiving circular buffer (5 ms) (section 6.2), *pd~* subprocess (2.9 ms), PD buffer delay (5 ms), and the UAD Apollo output latency.

Source	Latency
Bela input ADC buffer [18]	360 μs
Circular buffer (section 6.2)	360 μs
OSC and USB serial tx	
PD rx circular buffer (section 6.2)	5 ms
pd~ subprocess	2.9 ms
PD buffer delay	5 ms
UAD Apollo output latency	

Table 1: Latency sources and their known contributions.

With the measured sources totaling 13.6 ms, the soundcard and USB latency can be calculated at 13.4 ms. Additional latency is incurred with the use of the envelope follower: 5 ms, (for a total of 33 ms) likely introduced by the low-pass filter smoothing stages (section 5.2). Furthermore, the addition of FFT convolution adds latency equivalent to the length of the analysis window. For example, a 256-sample analysis window adds 6 ms (bringing the total to 39 ms of latency).

6.4.2 Pitch Detection Analysis. A comparative analysis was performed between *zDet~* and *sigmund~* to evaluate how the zero-crossing detector performed against an established industry standard within the context of the EV. The EV was tuned to standard viola tuning, and an ascending major scale was played on each string. *sigmund~* was used with default settings (1024-sample window, 512-sample hop size, and a 50,ms analysis delay). Each detector's output was sampled at 100 Hz during the performance. The two recorded output streams were re-synchronized to account for *sigmund~*'s inherent delay and charted in figure 7. In conclusion, *zDet~* performed comparably, with 50 ms less latency and fewer dramatic misreadings during note onsets.

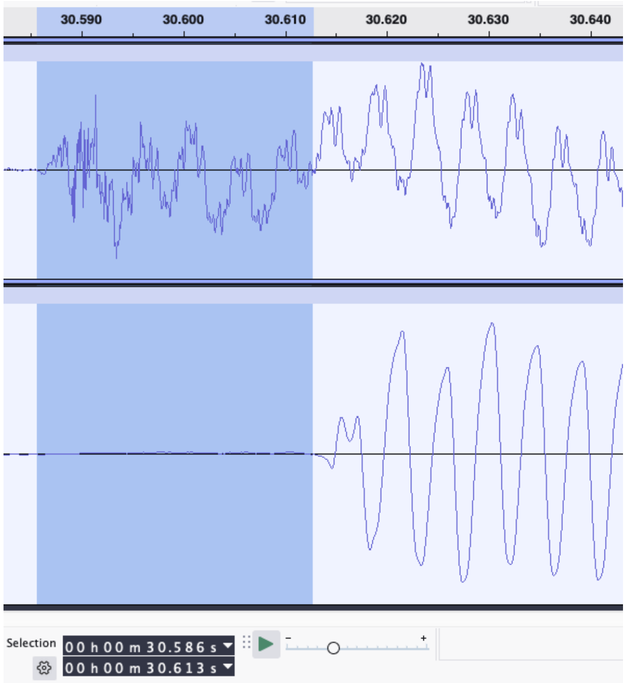

Figure 6: EV 2.5 Latency Measurement of 27 ms. Top track: EV string recorded via a microphone directly. Bottom track: the EV string via the IR pickup and passed unchanged through the EV system and output through a speaker.

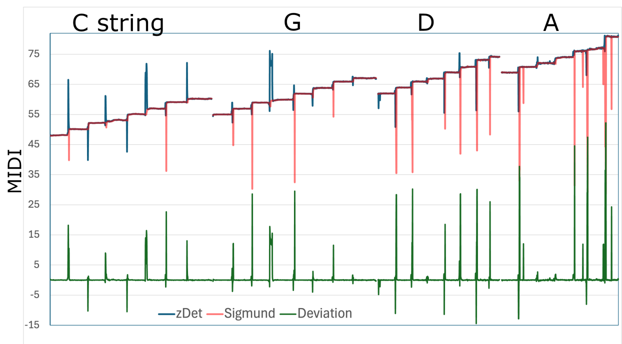

Figure 7: Frequency detection comparison between *zDet~* and *sigmund~*. A one-octave major scale is played on each string.

7 Future Work

The EV has developed into a robust tool for both studio and performance applications. That said, much work lies ahead in continuing to improve portability, latency, sensor accuracy, and aesthetic. The design for EV 3 is currently underway, aiming to address these issues.

EV 3 will be self-contained, with onboard processing handled by four Bela Minis (one per string). This design eliminates the need for a laptop and audio interface, simplifying setup. The GUI interface will be ported to a wirelessly-connected tablet application. An additional benefit will be reduced latency: the Bela's sub-2 ms round-trip latency [18] outperforms the current 27 ms (section 6). With a dedicated Bela per string, the audio input will be used, affording the use of the lower-noise delta-sigma converter. This is expected to improve the current SNR beyond the current 60 dB (section 6.4). In addition, this will hopefully solve an issue where the current envelope follower and *threshold~* object struggle to detect quiet notes close to the noise floor.

While the past two EV versions are 3D-printed plastic, EV 3 will be CNC-machined from curly maple. This will provide three improvements. First, it allows for a smooth, finished neck surface, as might be expected from a traditional instrument. In previous iterations, the bottom of the neck was buttressed by supports when printing, leaving a slightly rough feel. Second, the use of maple increases structural stiffness. Although tough PLA supported by carbon fiber rods was used for EV 2.5, the neck still flexed slightly under tension, a limitation the wooden construction is expected to overcome. Finally, the aesthetic of wood is valued in instrument design. It will be interesting to see how this material affects the instrument's visual presentation.

Although the use of embedded computing has many benefits, a drawback will be a limited processing capability. To mitigate this, the current PD software is being ported to an efficiency-oriented C++ version.

As the EV reaches a more refined state, user feedback surveys will be conducted. At this earlier stage, development has been driven by the author's own usage and reflective evaluation.

Lastly, there remain exciting software possibilities to be implemented—particularly physical modeling. EV 2.5 includes a rudimentary physical model based on the Karplus-Strong algorithm. However, the potential of physical modeling remains to be thoroughly implemented, aiming to explore the hybridization of real and virtual sound within composition.

8 Conclusion

Over the past four years, the EV project has evolved from an idea into a fully functional instrument with a distinct sonic identity. Initial experiments with EV 1 demonstrated the creative potential of cross-synthesis between the instrument's acoustic and electronic sound. Though constrained by rudimentary and unreliable hardware, the convolution algorithms revealed their capacity to carry the expressive nuance of a trained string player into the realm of synthesized sound. EV 2 aimed to address the many limitations of the initial prototype, particularly the constraints imposed by the retrofitted viola body and homemade circuitry. Embracing digital fabrication, the development of a custom-designed body and use of manufactured PCBs solved many issues of reliability. However, these changes also introduced a host of new problems, leading to the development of EV 2.5. Resolving the majority of hardware issues allowed the expansion of the instrument's software capabilities, opening the way for new sonic possibilities. The increased reliability allowed the instrument to be brought from the studio to the stage, imbuing the author's electro-acoustic compositions with the performance dynamics typically associated with live string performance. While much work lies ahead, the guiding question remains: What exciting new music is the EV creating right now?

9 Ethical Standards

This project was undertaken within the standards of the NIME Principles & Code of Practice on Ethical Research. The design and fabrication of the EV across versions 1, 2, and 2.5 involved iterative prototyping processes that necessarily generate material byproducts. Every effort has been made to minimize waste by repurposing components and reusing materials across versions wherever feasible. When reuse was not possible, components were recycled using the most responsible methods available. There are no observed conflicts of interest in this project.

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