The Electrosteel: An Electronic Instrument Inspired by the Pedal Steel Guitar

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ABSTRACT

The Electrosteel is a new electronic instrument inspired by the user interface of the pedal steel guitar (PSG). The Electrosteel uses the interface concepts of the PSG (a bar in the left hand, plucked strings for the right hand, foot pedals, knee levers, etc) as a control paradigm for digital synthesis. The instrument allows performers with skill on the PSG to expand their sonic range, and creates a powerful new multi-dimensional way to control synthesis. This paper describes the development of the instrument and its custom embedded synthesis engine, with a focus on the design challenges posed by mapping an existing performer interface to a new instrument.

Author Keywords

pedal steel guitar, slide guitar, synthesis, interface

CCS Concepts

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

Figure 1: The Electrosteel

1. INTRODUCTION

The initial sonic idea of the Electrosteel (Figure 1) was to enable the coupling of the musical gestures that the PSG's distinct interface makes possible with electronic sounds that are timbrally different, for instance 8-bit chiptunes synthesis. Unlike systems like the IVL Steelrider[1], which used pitch-tracking on a PSG and converted pitch information to MIDI, the Electrosteel employs a PSG-like physical interface to control synthesis directly, enabling the pedals and levers to do bends and timbral shifts that are physically impossible on a PSG.

2. THE PEDAL STEEL GUITAR

Invented in the mid-1950s, the modern PSG is a slide guitar with foot pedals and knee levers that alter the pitch of the open strings to shift which chords and intervals are available to the player. Ultimately a descendent of the Hawaiian lap steel guitar, its design was directly informed by pedal-activated instruments developed in the 1930s and 1940s such as the Gibson Electro-Harp and the Multi-Kord. For a detailed overview of its history, see Miller[16]. Today, it is most often associated with American country music, where it provides the expressive "crying" sound[3], marked by complex pedal glissandos, that is a strong signifier of the genre. Notable country players include Buddy Emmons (who is credited with many of the initial technical innovations that standardized the modern version of the PSG[6]), and Lloyd Green. It is also the central instrument in the "sacred steel" gospel tradition[23], with players like Robert Randolph pushing the instrument in a different stylistic direction, employing rapid-fire single-note voice emulation that could be compared to a bluesy shout. Unfortunately, outside of these genres, the instrument is very rarely heard. Notable exceptions include Susan Alcorn, who performs experimental music on the PSG, and Greg Leisz and BJ Cole who play pedal steel on jazz, pop, and rock recordings.

The PSG's unusual interface provides a remarkable level of control and subtlety. The bar – a sliding metal piece guided by the player's left hand – gives continuous control of pitch and vibrato. Pedals and knee levers allow players to bend the intervals between strings. Unlike the pedals on a concert harp, the PSG's pedals and levers create a continuous change. This allows the player to slide pitch independently of the bar, enabling chords whose notes move with independent speed and direction. Some electronic continuous MIDI Polyphonic Expression (MPE) interfaces like the Haken Continuum[8], the TouchKeys[15], or the Roli

[1]https://www.muzines.co.uk/articles/ivl-steelrider/807

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Seaboard[2], can achieve a similar effect through hand controls. However, the PSG's distribution of control among the hands, knees and feet preserves the independence of voices in a unique way. It also allows for vibrato to be easily synchronized between the voices, as the vibrato is created by the bar and applies to all strings. The Electrosteel seeks to offer the musician a similar mode of expression.

3. THE GOALS OF THE ELECTROSTEEL

The Electrosteel is an electronic instrument that mimics the performance interface of the PSG, while offering the expanded timbral world of a modern synthesis engine. The goal is to leverage existing sensorimotor skills of PSG players on the new instrument, enabling more rapid embodiment of the instrument for the player, and therefore increasing access to musical expressivity[7]. Unlike PSG MIDI pickups, for instance, the Electrosteel is not intended to, for instance, let a PSG player sound like a saxophone, but rather to put electronic synthesis under the finely expressive musical control that an experienced PSG player can produce. While the Electrosteel is not intended as a replacement for a PSG, there are some practical advantages when compared to a PSG. The instrument is much lighter and more portable than the PSG, which is notoriously heavy and cumbersome. Also, the Electrosteel's single neck is able to operate in several selectable tunings, while PSGs are often built with multiple necks to support different tunings. While there have been several electronic musical instrument that borrow inspiration from the slide guitar[9][19], and one that is inspired by the PSG[10], the authors are not aware of another instrument that approaches this concept with the depth of the Electrosteel.

4. IDENTIFYING THE IMPORTANT PSG INTERFACE FEATURES

The first task in the development of the Electrosteel was to determine which interface elements of the PSG were important to preserve, and which could be simplified or removed. By learning basic PSG techniques and some repertoire, the first author was able identify the essential elements that give the PSG its expressive potential. The following components were considered essential: The left-hand bar, right-hand plucking and muting, right-foot volume pedal, left-foot pedals, knee levers, and additional right-hand controls. The development of each of these elements of the Electrosteel is described below.

5. THE ELECTROSTEEL INTERFACE ELEMENTS

5.1 Left Hand Bar

On the PSG, the bar is held in the left hand and rests on the strings, which are strung about 7mm above the neck. On the neck there is a printed "fretboard" pattern to provide a visual reference for pitch location. While some players, such as Buddy Emmons, have trained themselves to be able to play without the fretboard reference[6], it is extremely unusual to do so. The feel of the bar in the hand is a major element of the performer's sense of the instrument - and the weight and shape of the bar contribute to the left-hand gestures used by players. This suggests that an interface that seeks to capture this expression should include an actual physical bar, and a sensor to read its position on a neck that features visual fret markers. The naive solution to the bar position problem would be a voltage-divider approach, with the linear strip connected to power and ground at each side and the bar forming the wiper. Unfortunately, this is not usable since the left hand rests on the strings behind the bar, confounding the readings, so another approach is needed. The first attempt at an emulation of the bar interface was the employment of a single commercially available "soft pot" linear position sensor. Unfortunately, actuation force was too high to provide comfortable slide gestures, as it required the player to press down harder on the sensor than standard PSG technique calls for. The next iteration involved a custom sensor inspired by the soft pot technology and ribbon controllers: a resistive strip was printed on a custom PCB using carbon ink, and a guitar string was strung above it, with only a 1mm gap between them. In performance, the bar presses the string to the resistive strip, closing the circuit. The side of the resistive strip closest to the bridge is driven with a constant-current DAC at a low current (50uA) through a fixed resistor, and the string is grounded. With this technique, the ratio between the voltage across the variable resistance and the voltage across the fixed resistance is reasonably linear (Figure 2).

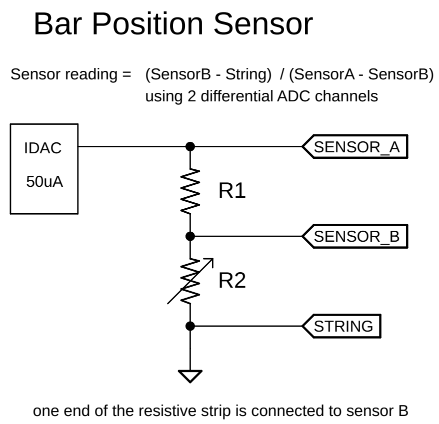

Figure 2: Circuit to sense the linear bar position

This was found to be effective, although the actuation force is still slightly higher than a player would expect. Also, higher bar positions require more actuation force, since the string must be raised more at the bridge position to make sure the string rises from the sensor PCB at a clean angle from the bar.

Once the instrument was playable, it was determined that a single sensor for the bar is not enough for some modes of playing. To allow for "bar slants" and subtle variations of the bar angle across the strings, a second sensor was added to the neck, and the position between the two sensors interpolated to find the position of the bar over each virtual "string". Higher numbers of linear position sensors were tried but any number of sensors beyond two increases the likelihood that a sensor won't be pressed enough if the strings aren't completely level on the neck, and the added sensor noise was determined to be not worth the additional data.

From the player's perspective, two simplifications on the left-hand bar interface of the Electrosteel are particularly noticeable and require some player adjustment from their PSG technique. One is that a PSG player actually moves the bar toward and away from their body as they play, only

[2]https://roli.com/products/seaboard/rise2

pressing the bar against the highest string they are actually sounding. On the PSG, this serves two purposes: it produces the cleanest tone from the bar and it allows the fingers of the left hand that fall behind the bar to mute higher strings as the bar is moved closer to the player. This motion is unnecessary on the Electrosteel, and actually would cause the player to move the bar off of the strings. The fact that "left-hand muting" with the fingers is not possible on Electrosteel can be a serious issue if the player relies on that technique. There are several schools of thought on muting in PSG practice, and some players avoid this muting style, so this simplification will affect some more than others. The other important simplification is that on a PSG, the player can put the bar over some strings and leave other strings open. This is not possible with the two-sensor system that is currently on the Electrosteel, but it is also a relatively uncommon technique on the PSG.

5.2 Right Hand Plucking System

On the PSG, the right hand technique is one of the most difficult parts of the instrument to master. The sustain of the strings is very long, so to play single-note lines cleanly, one must constantly be muting the sounding strings at the exact moment that a new string is plucked. For the Electrosteel, a decoupling of decay time and sustain level from the physical realities of a vibrating string was desired to increase the flexibility of the sound synthesis. Therefore, the goal of the right-hand plucking system was to detect pluck events (with amplitude) and mute events, but nothing further.

PSGs usually have either 10 or 12 strings. Any reduction in the number of strings for the right hand would make normal PSG playing technique impossible, so it was decided to design a 12-string system (10-string players can remove the bottom 2 strings). While there are many possible technologies that could be used, such as a set of piezo film flaps or buttons to represent the strings, the feel of the strings under the fingers is an important touch cue for playing the PSG, so the decision was made to preserve that as much as possible. A short set of 12 strings was strung over a bridge and nut (Figure 3) under the right hand position, damped with felt on both ends. To reduce crosstalk, optical IR reflectance sensors were used to detect string motion (QRD1113), since the IR light could be blocked between strings more easily than electromagnetic fields. However, this only works well if the strings are relatively thick and very close to the sensors, meaning that the strings cannot be the standard gauges PSG players are used to. Tests with PSG players found that this was confusing as they often use the transition from wound to unwound strings as a visual place marker to keep their orientation on the many strings. Also, the IR sensors are particularly sensitive to positioning (which the felt damping makes less reliable) so it is likely that a future version will switch to single-string electromagnetic pickups and work to reduce crosstalk in other ways. Another potentially interesting solution would be piezo strings [5], if the technology evolves to allow for normal string tension.

Plucks are detected using a relatively simple envelope detection algorithm, running on an STM32H750 microcontroller. The 12 strings are sensed by the built-in ADC, and when a pluck is sensed, an SPI message is sent to a PSOC5LP serving as the "brain" MCU.

Muting was achieved by having the strings themselves serve as capacitive touch sensors. A PSOC5LP microcontroller performs both the string-muting sensing and the bar-position sensing, and sends these signals to the "brain" MCU via SPI.

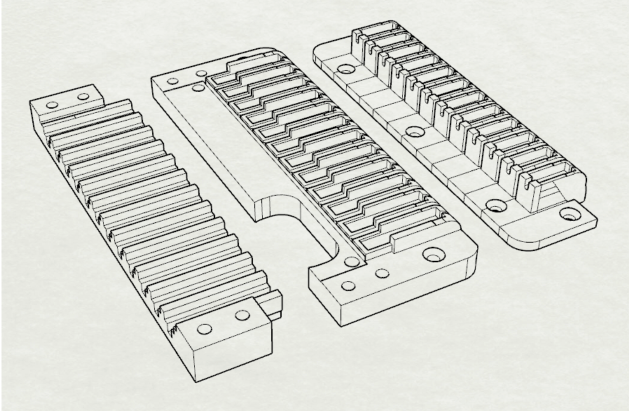

Figure 3: Design drawing of the bridge cover, bridge, and nut for the right-hand strings

5.3 Right-Foot Volume Pedal

While for standard guitar a volume pedal would be an optional accessory, on the PSG it is an integral part. The volume pedal has been a necessary feature of the instrument since the 1950s, and there is a particular technique for increasing the perception of sustain by easing up the volume after striking the strings, a kind of "manual compression". On the Electrosteel, an expression pedal was substituted for this so that it could affect parameters beyond volume. Accordingly, a miniature expression pedal is connected to the left-foot pedal board by a TRS cable, where it is sensed by an ADC.

5.4 Left-Foot Pedals

The left-foot on a PSG activates a set of between three (3) and eight (8) pedals that connect via metal rods to the underside of the instrument. These rods, through a series of mechanical linkages, pull on a set of individual per-string bridges, called the changers, which rotate on a fulcrum to adjust the tension on the string. Since there is no need in the Electrosteel for actual mechanical changing of string length, simplification of this mechanism, while preserving the feel and functionality for the player, was desirable. The pedal and changer simplification accounts for much of the weight difference between Electrosteel and the PSG. Over the course of the Electrosteel project, the left-foot pedal system proved to be the most difficult design challenge on the instrument.

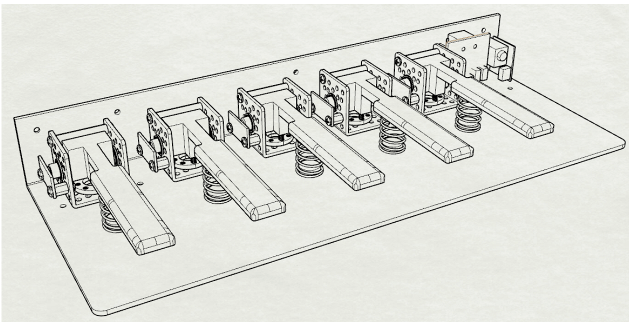

Figure 4: Design drawing of the left-foot pedal system, uncovered

The first and simplest iteration for the proof-of-concept version was simply a plywood board with the pedal mechanisms from three Yamaha FC3A continuous sustain pedals attached to it. These foot pedals are designed to be used with an electronic keyboard that senses half-pedaling, so they are actually a continuous potentiometer-based pedal, rather than a switch. They were somewhat larger than the pedals on a PSG, so the spacing between them was not ideal, but they worked well enough for initial tests. The next iteration, and first custom solution, used 3D-printed plastic parts for the pedals and the mounting hub, with potentiometers for sensing the pedal angle and small extension springs to return the pedal to its initial position. Later iterations abandoned the direct potentiometer approach, to avoid reliance on the shaft connection of the potentiometer as a mechanical support, and due to concerns about rapidly wearing out the resistive material in the potentiometers, as the pedals are moved constantly in normal playing. The potentiometers were replaced with angular hall sensors paired with magnets glued to the end of the shafts. The shafts were supported on sets of ball bearings, and the pedals were affixed to the shafts with set screws.

Figure 5: Photograph of the left-foot pedal system, with enclosure cover in place

Many of the iterations of the foot pedal system were motivated by the need to replace plastic parts with metal for increased rigidity, as the pedals take significant forces in many different directions (the player may roll their foot onto a pedal from either side, or come down from the top, for instance). The shape of the pedals themselves also underwent much iteration, as the original square edges were found to catch on shoe soles, and needed to be rounded off. The small extension springs were replaced with larger compression springs underneath the pedals, a design feature borrowed from the Yamaha FC3A, and one that made switching out the springs to adjust spring strength easier for the player. The final system used custom CNC-milled aluminum parts for the pedals and off-the-shelf aluminum parts for the bearings, shaft, and mounting block (Figure 4).

The mounting block that holds the shaft is fitted with a custom part that allows for set screws to adjust the stop points for the resting and pressed positions of the pedals, which must be adjustable by the player and therefore needed to be exposed on the design. This is because PSG performers tend to set the pedals to different heights relative to each other by their own preference (for instance: first pedal slightly higher resting state than second pedal). Since the start and stop data are relative and can be changed by the user, the brain MCU of the instrument has a calibration mode that can record the range of the pedal data and store it in EEPROM.

The earlier revisions were housed in a custom cut 5mm thick aluminum enclosure, but the final revision replaced this with a custom bent steel enclosure design to reduce thickness and part count. The enclosure features a TRS jack to connect the external right-foot volume pedal, and an RJ-45 jack to connect the pedal system to the brain of the instrument through a standard ethernet cable (though the actual signal protocol reporting the hall sensor and expression pedal ADC data is I2C).

Since the number of foot pedals on a PSG is not standardized, it was difficult to decide on how many pedals the Electrosteel should have. Three pedals is enough for many things, but more pedals allow for more flexibility. The Electrosteel prototype began with three pedals, grew to 7 pedals at one point, and then settled at 5 pedals in its last iteration as a compromise between flexibility, cost, and weight.

5.5 Knee Levers

In the early 1960s, knee levers became common on the PSG. Like the left-foot pedals, these levers are used to change the pitch of the open strings. Most PSGs have at minimum two knee levers, although some have up to 8. 5 is a common complement of knee levers, as it can include levers in the left and right directions for both knees, as well as a single vertical lever for the left knee. Beyond this, PSGs sometimes include “inner” and “outer” levers for the same direction on one knee, meaning separate levers that are closer or further from the player, although these are generally harder to activate independently. A vertical lever on the right knee is harder to use because the position of the foot on the volume pedal allows for less knee flexibility. A complement of 5 levers was decided upon as a reasonable amount for the Electrosteel, providing the most flexibility before the added complexity begins to be hard to justify.

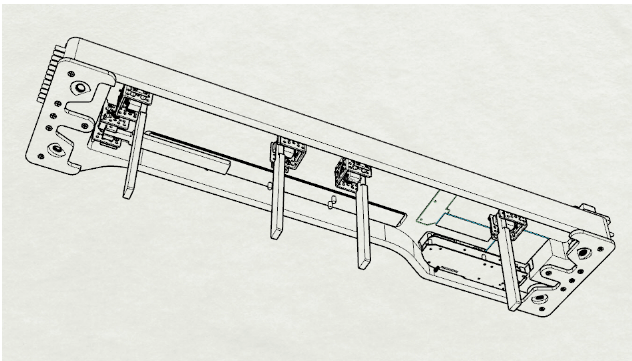

Figure 6: Drawing of the Electrosteel, underside view

As the knee levers add significant cost and mechanical complexity to the instrument, one early idea for the Electrosteel was to manage the functionality with a greatly simplified system, such as IR position sensors for the knees, or something else that eliminates moving parts. Unfortunately, this is not realistic if the goal of harnessing existing embodiment from PSG technique is taken seriously, as the physical feedback of the knee lever moving and its resistance to movement is an important part of controlling the instrument[21]. Even more important is the existence of me-

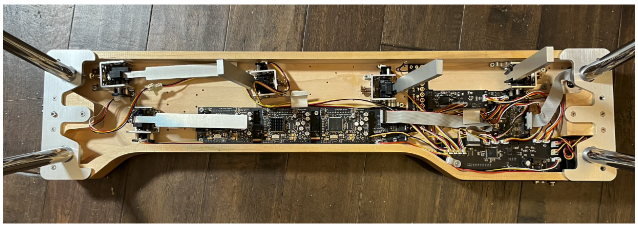

Figure 7: Photograph of the Electrosteel, underside view

chanical stops to end the lever travel so that exact pitches can be arrived at following a glissando. Therefore, it was clearly necessary to build a mechanical knee lever system to provide the proper feedback to the player, even if this mechanical system was only resolving into a relatively simple sensor reading.

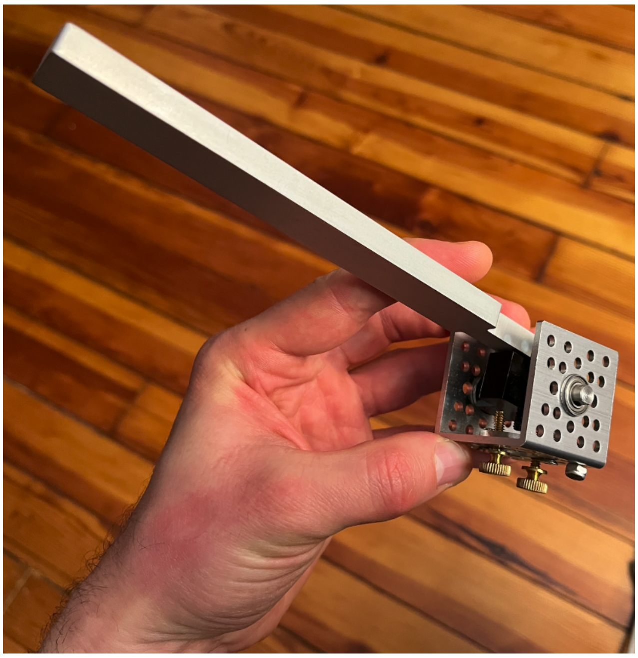

Figure 8: An Electrosteel knee lever mechanism

With this in mind, one early design goal was to have as much reuse as possible between the left-foot pedal system and the knee levers, as they are almost the same thing, just rotated 90 degrees. The foot pedals protrude parallel to the ground toward the player, and the knee levers emerge from the bottom of the instrument and hang downward, but their range of travel is similar. This goal was achieved to some degree, as the hall sensor, mounting block and shaft design could be reused easily, although changes were needed for the levers themselves. While the foot pedals could be constructed as a single part mounted to the rotating shaft by a set screw, the knee levers needed to fold up under the instrument for transport, necessitating another point of rotation. The knee levers were therefore fabricated as two parts: a hub and a lever (Figure 8). The lever is connected to the hub with a shoulder screw that allows it to pivot in one direction. The hub is then connected to the rotating shaft with a set screw. For the knee levers, the small extension spring version of the return system was needed, since there is no readily available surface against which to place a compression spring. On a PSG, there are points for adjustment on the knee levers available to the player via set screws to allow the instrument to accommodate players of different body sizes. This design was copied on the Electrosteel, with each knee lever hub featuring a set screw that angles the lever toward the player. This allows the mounting blocks to be relatively far from the center of the player's leg, and therefore able to be adjusted for leg size and position.

5.6 Additional Right-Hand Controls

It was determined that additional controls not present on a PSG would be useful on the Electrosteel. While the pedals and knee levers could provide a powerful collection of timbre controls for synthesis, if a player is instead using them to manipulate pitch as on a traditional PSG, then a set of knobs would be helpful to adjust other synthesis parameters. While this is motivated primarily by the fact that the sound palette of the Electrosteel can be far wider than the PSG, it is also especially needed because the Electrosteel interface loses some of the most important timbral controls of the PSG instrument, such as sensitivity to plucking position on the string. For this purpose, near the right hand, the Electrosteel features a panel with two knobs, labeled A and B, and a small 2D joystick. Other functions were added as needed, such as octave buttons and an OLED screen for synthesis preset loading.

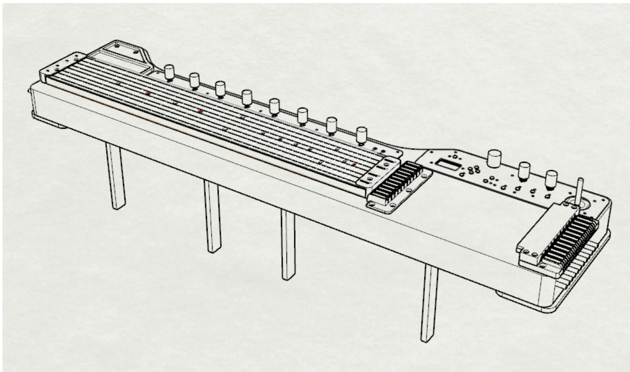

Figure 9: Drawing of the Electrosteel, top view

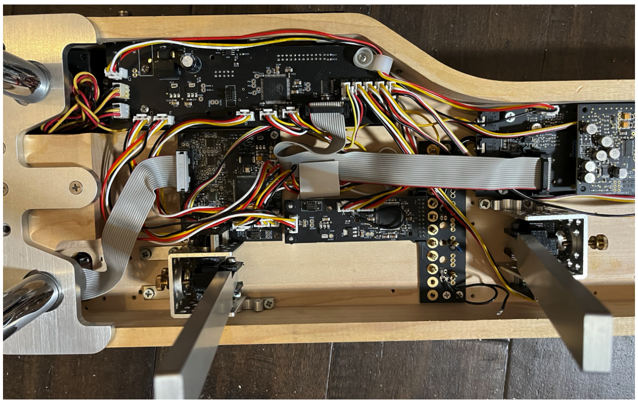

Figure 10: A closer photograph of the circuitry inside the Electrosteel body

6. AUDIO SYNTHESIS ENGINE

Since the goal of the Electrosteel was to allow electronic synthesis to be controlled with the expressivity of the PSG interface, it made sense to create a digital synthesis engine that was designed to take advantage of the control the Electrosteel offered. Early prototyping treated the Electrosteel as an MPE USB-MIDI controller and interpreted the incoming data with Max-MSP patches and various commercial software synthesizers that could respond to MPE data (necessary due to the independent per-string pitch bend capability). This was useful when testing the sensor data and mechanics of the instrument, but the ultimate intention was always to have a custom synthesis engine embedded in the instrument. Later revisions achieved this goal, with onboard synthesis algorithms producing digital sound and sending the audio signal to a 1/4" TS output jack on the Electrosteel front panel.

Embedded synthesis was implemented using the first author's Genera Audio Board, a development board that includes an STM32H743, an audio codec, SDRAM, and a microSD card slot. The requirement for 12-note polyphony, which was crucial for enabling traditional PSG playing on the Electrosteel, was a significant challenge. A custom PCB was designed which housed three Genera Audio Boards, so that each would only need to serve 4 notes out of the 12.

Three methods of embedded synthesis were initially tested on the prototype: subtractive wavetable synthesis, additive synthesis, and physical modeling. All three methods were implemented using the first author's LEAF C audio library (Lightweight Embedded Audio Framework), and found to be promising. For additive synthesis, a PSG's plucked strings were recorded at several positions on the neck on each string. The decay times of the harmonics for each pluck were analyzed in SPEAR[13], and a table of these decay times was used to extrapolate envelopes for a set of sine waves. This produced a relatively realistic PSG tone, even reproducing the darkening of the tone color as the bar is moved up the neck, since the bar position was maintained as a separate variable from pitch. Missing from the simulation were more subtle effects like pick noise, inharmonicity, and phantom harmonics. Lastly, a physical modeling approach was attempted and found to be very effective. The string model used was based on the living string model by Dahlstedt[4], with several modifications based on research from Smith[22], Lasko [14], Valimaki [24], and Karjalainen [12]. After developing these three synthesis methods, it became

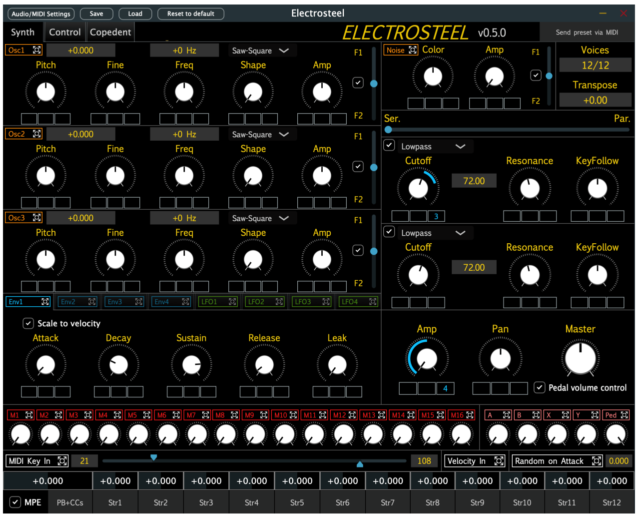

Figure 11: The Electrosteel synthesis plugin

clear that more flexibility in the synthesis design for the end user was needed. We began to develop an audio plugin that would enable the user to configure a specific synthesis preset on a computer, load it to the Electrosteel, and call it up later in performance(Figure 11). This became the Electrosteel plugin, created in C++ using the JUCE library[3], and primarily developed by the second and third authors Matt Wang and Davis Polito at the Princeton New Instrument Research Lab (NIRL). So far only the subtractive synthesis method has been built into the plugin. The plugin features three hard-syncable oscillators with selectable waveshape[2], a filtered noise section, two filters with selectable algorithms[25], a set of 4 mappable LFOs and 4 envelopes, a final VCA, and an FX section with a variety of processing options (compression, bitcrushing, etc). Most parameters can be mapped by the user to be controlled by one of the possible modulation sources, which range from the oscillator outputs (enabling FM effects) to the joystick on the panel. When a synthesis preset has been designed using the Electrosteel plugin, it can be loaded onto the embedded hardware over USB-MIDI sysex and stored as one of the user synthesis presets on the instrument's internal microSD card. While this synthesis method was powerful, it was too computationally intensive for 4-voice polyphony per audio board. It was deemed worth adding more parallel processing to make it possible, so the number of audio boards was increased to 6, letting each board handle only two voices.

7. COPEDENT DESIGN

On a PSG, the configuration of which pedal or knee lever does what change is referred to as a copedent (for ChOrd-PEDal-ArrangemENT). One of the most exciting capabilities of the Electrosteel when compared with a PSG is the ability to change the copedent on the fly. On a PSG, changing the copedent often must be done by a technician, and will usually take at least a day. There are also physical limits to what a pedal or lever can do, as the number of strings changed increases the stiffness of the pedal action, and most strings can only be altered up or down by at most a minor third. These limitations are nonexistent in the Electrosteel, but an interface was still needed to allow the player to configure new copedents as easily as possible. This was built into the Electrosteel plugin with a copedent editor tab (Figure 12) that lets the user enter the pitches of the open strings and all the changes that each pedal or lever causes.

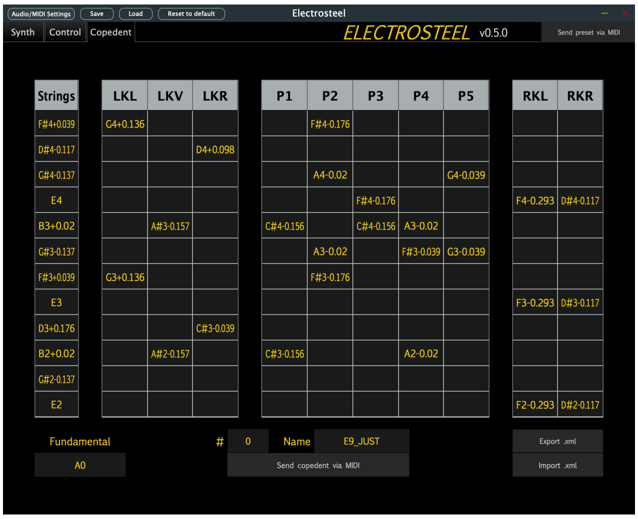

Figure 12: The Electrosteel plugin copedent settings window

In the interface, pitches can be entered as note names with cents deviations (such as C4 + 4), MIDI notes (such

[3]https://juce.com/

as 60.04), or pitch ratios (such as 5/4). Internally, all values are converted to fractional MIDI notes (such as 60.25). Copedents are sent over USB-MIDI sysex messages to the Electrosteel for storage on the brain MCU EEPROM.

8. RESULTS

The Electrosteel had been played constantly during its multi-year development, but its first public performance occurred on January 3rd, 2023 at the Red Room in Baltimore. It was played by the first author in an improvisational duo with another electronic musician, and proved to live up to the authors' hopes for the instrument. However, now that the instrument is in a mature state, more user data is needed to determine the success and usefulness of the instrument. During the development phase, one professional PSG player tried it out and gave valuable feedback, and more feedback of this type is needed.

The PSG is both a rare and a famously difficult instrument, and that combination means that there are few skilled players in the world. Since the Electrosteel is designed to take advantage of PSG skill, the most useful data in the future will be from professional performers who test out the Electrosteel in their own practice. This is the next goal of the project.

9. CONCLUSION AND FUTURE WORK

There are several aspects of the instrument that need improvement. The left-foot pedal box currently slides on some surfaces, so the addition of a "pedal-bar" to hold it in place is likely necessary. The left-hand bar sensing system could use improvement, as it requires slightly more effort from the player than a traditional PSG. Perhaps a bar that is sensed directly rather than indirectly through strings pressed against a circuit board would give a better feel, so magnetic position sensing through hall sensors or other location sensing could be used.

The next step on the plugin is to integrate the physical modeling synthesis and additive synthesis into the plugin interface, so that they can be configured as easily as the subtractive synthesis.

Another plan is to develop the physical modeling synthesis further to take into account other effects such as bar friction noise[18], phantom partials[1], inharmonicity[20], and electromagnetic pickup modeling[11][17] . The most important next step is to get the instrument in the hands of more players and receive feedback on where it excels and where it fails. We have the parts made for a set of 10 Electrosteels, and a list of players who are interested in borrowing one to test for their own musical uses. It is anticipated that this will reveal shortcomings and opportunities that the designers have not yet noticed.

Now that the Electrosteel is fully playable, the most pressing future work is to create music for it, both composed and improvised, and in multiple genre contexts, to see where it shines and where its unique features are most useful.

10. ACKNOWLEDGMENTS

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11. ETHICS STATEMENT

This project was undertaken within the standards of the NIME ethical code of conduct. A formal user study was not conducted as part of this research, so no ethical issues relating to study subjects were encountered. The authors acknowledge that this work does, however, make use of industrial fabrication processes (custom PCB fabrication and assembly, anodizing aluminum, etc) which contribute to environmental damage.

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