A Hybrid Guitar Physical Model Controller: The BladeAxe

Romain Michon
CCRMA, Stanford University
CA 94305-8180, USA
rmichon@ccrma.stanford.edu

Julius O. III Smith
CCRMA, Stanford University
CA 94305-8180, USA
jos@ccrma.stanford.edu

ABSTRACT

The BLADEAXE is a guitar-like controller that uses "real world" audio excitations from six piezoelectric films (one per "string") to drive a physical model of a guitar on a laptop. The BLADEAXE body is made out of laser cut acrylic sheets and can be easily reproduced. As a fully "plug and play" interface, it can be used on any computer to communicate with our open-source virtual-guitar software.

1. INTRODUCTION

Physical modeling of musical instruments has been a very active field since the middle of the 1980's and the discovery of the waveguide sound synthesis technique [1]. Since then, physical models of musical instruments became increasingly sophisticated and efficient giving birth to dozens of commercial product like Yamaha's *VL1* synthesizer series, [1] and plug-ins such as *Pianoteq*. [2]

Unlike many other synthesis techniques and like "real world" musical instruments, physical models need to be controlled in a very accurate way in order for them to produce realistic sounds. For example, a very advanced physical model of a trumpet will probably sound very bad if its parameters (pressure, lips tension, etc.) are not controlled properly and as a function of each other. On the other hand, very simplistic physical models can sound very good with advanced parametric control.

The difficulty of this control remains prohibitive compared to the simplicity of the reigning MIDI standard where the control of virtual musical instruments is often limited to "frequency" and "amplitude". Three different kinds of approaches to solve this problem have been implemented in the course of the last twenty years.

The earliest one was introduced by Yamaha with the *VL1* synthesizer series where a breath controller was used to increase the level of expressivity when playing wind instrument physical models. In this case, the velocity of the excitation was controlled by the breath of the performer and computed in the model, offering a very high level of control. The drawback of this technique was that it could only be used in the context of a live performance.

Another approach consists of modeling instrumental gestures to control the different parameters of a physical model [2]. This technique provides very good results and doesn't require a performer.

More recently, another solution was proposed to construct hybrid interfaces to control physical models of musical instruments. Different approaches can be taken but the main idea here is that a "real world" excitation (the sound of a pluck on a guitar, the sound created by a mouthpiece on a clarinet, etc.) can be used to drive a virtual string, a bore, etc. This technique was applied to clarinet [3], drums [4] [5] and to string instruments [6] [7] synthesis successfully.

For many musical instruments, the excitation is one of the hardest components to model and offers a very large number of parameters to control. With this last approach, only the resonant part of the instrument is computed, making the physical model much simpler. In the case of the *Kalichord* [7], a set of piezoelectric films can be plucked to drive a simple Extended Karplus-Strong model [8, 9]. The resulting sound is surprisingly good, realistic and expressive. It is almost as if the performer were able to physically touch the physically modeled string with his fingers.

In this paper, we present the BLADEAXE: [3] a guitar physical model controller, based on the same technique as the one used in the *Kalichord*. The BLADEAXE is made out of laser cut acrylic sheets. It is a fully "plug and play" USB interface that can be used to control physical models running on a laptop. It uses a six-channel Analog to Digital Converter (ADC) [4] to digitize the sound of the piezoelectric films, and an Arduino Due [5] to retrieve data from the different sensors/controllers placed on the neck and the body of the interface (see Figure 1 on page 7).

2. PLUCKING SYSTEM

2.1 Hardware

The plucking system of the BLADEAXE is based on six independent piezoelectric films: one for each string. We chose to use *SEN-09196* [6] because of their reasonable cost

[1] http://www.soundonsound.com/sos/1994_articles/jul94/yamahavl1.html
[2] https://www.pianoteq.com/.

[3] More practical information, videos and sound examples can be found the BLADEAXE website: http://ccrma.stanford.edu/~rmichon/bladeAxe.
[4] The six channels ADC is made out of three *Behringer Guitar Link UCG102* connected in parallel.
[5] http://arduino.cc/en/Main/ArduinoBoardDue
[6] http://dlnmh9ip6v2uc.cloudfront.net/datasheets/Sensors/ForceFlex/LDT_Series.pdf

(about three dollars each), their simplicity, and also because they are very common on the market and thus easy to replace.

Each piezo is glued to the middle of separate polycarbonate sheets (see Figure 3). The height and the thickness of these sheets were chosen to approximate the elasticity of a guitar string. Each sheet is placed in parallel and is 3/8" apart from its neighbors (corresponding to the distance between the strings on a "real" guitar).

Piezoelectric films are very sensitive to electromagnetic fields like the one created by the human body. Thus, they were shielded with grounded copper tape to prevent disturbances in their signal. Two additional bands of copper tape are used on each side of the piezoelectric film as capacitive touch sensors to detect if the skin of the performer is touching the piece of polycarbonate. This system is used to damp the virtual strings when they are not plucked and to detect the plucking position of the player (§3 provides more details on the way this system works).

Each piezo is connected to an independent preamplifier that also takes care of canceling DC. Indeed, when a constant pressure is applied to a piezoelectric system, it creates a continuous current which might create undesired behaviors in our case. Also, each preamplifier contains a lowpass filter with cut-off frequency at 10 kHz. Indeed, piezoelectric films have a very strong resonance peak at around 16 kHz [7] and it is crucial to eliminate this part of the spectrum of the signal before feeding it into a waveguide.

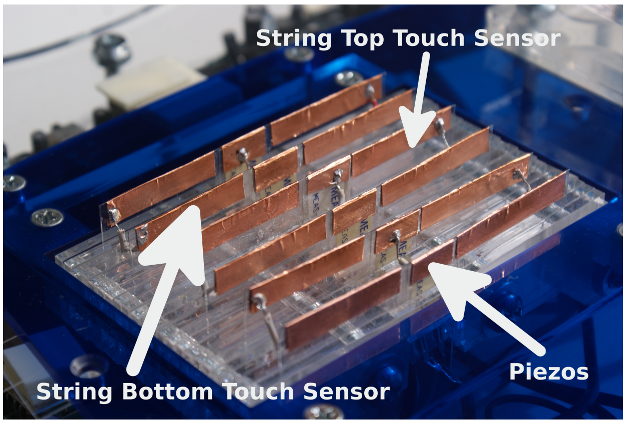

Figure 3. The plucking system of the BLADEAXE. We can see the three bands of copper tape on each "string" used to detect the plucking position and to minimize the impact of electromagnetic fields on the piezoelectric films signal.

Finally, the output of each preamplifier is independently digitized and sent to the laptop to be fed into the physical model. The sampling rate of the system is 32KHz which is more than enough as the analog signals of the piezos are bandlimited to 10KHz by the preamp's lowpass filters.

The plucking latency is fully determined by the ADC latency which is about ten milliseconds on the BLADEAXE. This is fine for most cases but it could be improved by using a better ADC.

[7] http://en.wikipedia.org/wiki/File:Piezoelectric_sensor_frequency_response.svg

2.2 Pluck Sound Analysis

The nature of the impulses created by the finger when plucking one of the polycarbonate sheets can vary a lot as a function of the pluck type. This is what makes the sound of the BLADEAXE so realistic. For example, the impulse will be different if the pluck is carried out with a nail, the skin of the finger, a bow, etc., just like on a "real" guitar.

Similarly, the position of the pluck also matters a lot: if the polycarbonate sheet is plucked on one of its extremities, the impulse will contain more high frequencies than if it is plucked in the middle. The consequence of this is that the virtual string will sound like it is plucked closer to the bridge or to the nut if the piece of polycarbonate is plucked on one of its sides!

As the two sides of the polycarbonate sheet sound the same, the capacitive touch sensors are used to determine if the impulse was created closer to the bridge or to the nut. A digital filter is applied to the impulse as a function of this parameter (more details on this point are provided in §3).

Figure 4 shows the waveform of a pulse created by plucking one of the polycarbonate sheets of the BLADEAXE on its upper side with the skin of the thumb. The first 10 ms corresponds to the rubbing of the skin of the sheet followed by the pulse and a very short resonance. The copper tapes used for the capacitive touch sensors help greatly to damp the polycarbonate pieces and therefore suppress their natural resonances.

Figure 5 shows the FFT of the pulse presented in Figure 4. As expected the spectrum is very dense and has a comb like shape. There are a few frequency peaks near 2000, 3200 and 7200 Hz. If a pulse is created by plucking the polycarbonate sheet at the middle (on the piezoelectric film), a very similar spectrum is generated except that it is shifted downward: the first frequency peak becomes 1600 Hz, etc. This behavior is close to the one modeled by the pick position comb filter described in [10].

This is just an example. Indeed, a full analysis of the behavior of this polycarbonate-sheets plucking system could be carried out, but this is not the object of this paper.

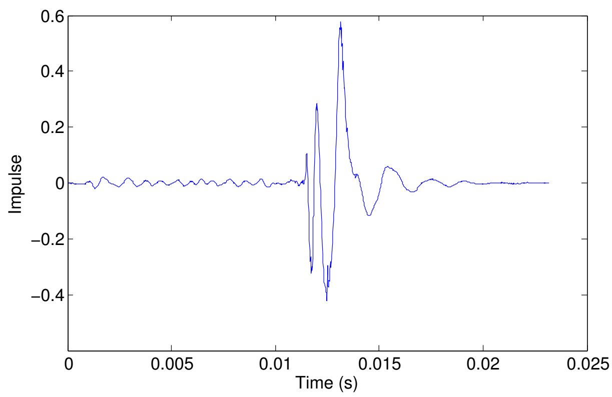

Figure 4. Waveform of a pulse created on one the polycarbonate sheet of the BLADEAXE plucking system. The pluck was carried out on the upper side of the sheet with the skin of the thumb.

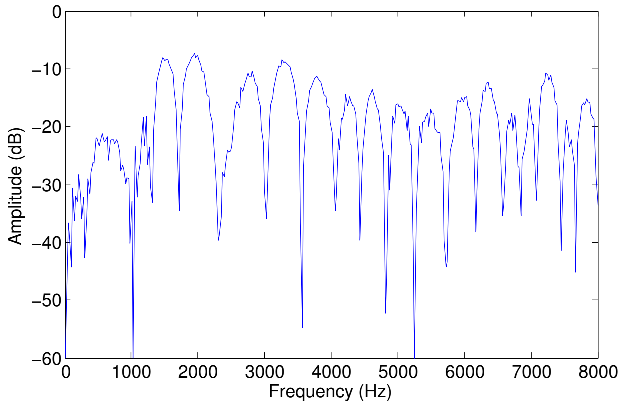

Figure 5. Fast Fourier Transform of the signal of the pulse presented in figure 4.

3. THE PHYSICAL MODEL

The guitar physical model of the BLADEAXE is based on *Free Axe* [10]. It has six parallel virtual strings connected to a series of effects such as an amplifier and a speaker model, a distortion, a chorus, a flanger, etc. The model is implemented in FAUST [8] and is running on a laptop as a standalone *ALSA* [9] application.

The *Arduino Due* that retrieves the data of the different BLADEAXE controllers placed on the neck and on the plucking system (capacitive touch sensors) runs a custom firmware that sends serial OSC [10] messages to the physical model software. Serial USB is extremely fast so the different BLADEAXE controllers have almost no latency. Also, the use of OSC with serial makes the system very portable and "plug and play".

The digitized signals of the piezoelectric preamps are first lowpass filtered at 10KHz to make sure that the preamp analog lowpass filters removed the peak around 16KHz. Next, a noise gate lets the signal drive the virtual string only if it reaches a certain level. Indeed, our preamplifiers tend to generate a little bit of noise (less than -55dB). This system prevents the noise from making the virtual string vibrate if it's not plucked.

After this step, the signal goes through a pick position filter (a simple feed-forward comb filter) [9]. The coefficients of this filter are computed as a function of the pluck position detected by the capacitive touch sensors on the polycarbonate sheets.

Finally, the signal is fed into the virtual string whose different parameters are controlled by the neck. An overview of this process can be seen in Figure 1 on page 7.

4. THE NECK

Designing a neck for the BLADEAXE that offers a level of control similar to that of a real guitar fretboard proved more complicated than we expected, and we constructed several prototypes before finding a satisfactory solution.

[8] `http://faust.grame.fr`
[9] *Advanced Linux Sound Architecture*: `http://www.alsa-project.org/`
[10] *Open Sound Control*: `http://opensoundcontrol.org/`

4.1 Guitar Neck Taxonomy

On a real guitar, the neck enables changing the length of the strings in order to modify the frequencies of their fundamental modes of vibration—in other words, their pitch. For that, the guitarist can press the strings against different frets, shifting the position of "the nut termination" of the string.

A standard guitar neck contains twenty-four frets placed one semitone apart from each other covering two octaves on each string. Frets are not equidistant, but rather get closer as we go up the neck. This feature has two important consequences on the technique used by a guitarist. First, one has to remember intuitively that frets are not equally spaced. But more importantly, it is much easier to play chords near the bottom of the neck where the fret-spacing is larger.

These are the main parameters that we tried to take into account to design the BLADEAXE neck. More information on the physics and design of guitar necks can be found in [11].

4.2 Guitar Neck Features

Let's try to establish a non-exhaustive list of the general features offered by a "real" guitar neck:

- In the absence of bending, the pitch of each string is changed by semitones.
- The pitch of a string can be bent up by two semitones or more by sliding the string along a fret with the finger stopping the string. This technique can be used also to add vibrato.
- The amount of pressure applied to a string by a finger enables the player to switch between two modes of vibration: if the string is just touched but not pressed against a fret, the fundamental will be canceled and only the harmonics will be heard. If the string is pressed against the fret, the termination of the string becomes stiffer and the fundamental can be heard.

4.3 Abandoned Neck Prototypes

While designing our different neck prototypes, we tried to find the best solutions to implement the different features mentioned in the previous section. Dozens of technologies usable to create a controller that would meet our needs and expectations to design a good guitar virtual neck are available on the market. Their quality and price can vary a lot. Our goal was to build a precise controller that would provide sensations close to those offered by a "real" guitar neck and keep it cost effective.

Ideally, a guitar neck based on a technology similar to the one of the *LinnStrument* [11] would have been excellent. Unfortunately, this system greatly exceeds our budget, due in part to the fact that a customized version of it would be required.

[11] `http://www.rogerlinndesign.com/preview-linnstrument.html`

In the following subsections, we present the different BLADEAXE neck prototypes leading to the final version.

4.3.1 Soft Pot Based Prototype

Our first prototype (see Figure 6) was inspired by the technique used in the *GXtar* [12], where a soft pot [12] is used to detect the position of the finger on the neck. The main advantage of using soft pots is that they provide a continuous control. Unfortunately, they are not precise enough to create a good vibrato. They also present many other handicaps:

- Large soft pots (500mm) can sometime have unpredictable behaviors which makes them almost impossible to use in a concert context.
- Commercial large soft pots are too wide to be placed in parallel to make a six-string virtual guitar neck and "handmade" soft pots are hard to make.
- Commercial large soft pots are relatively expensive sensors (about $30 per unit).

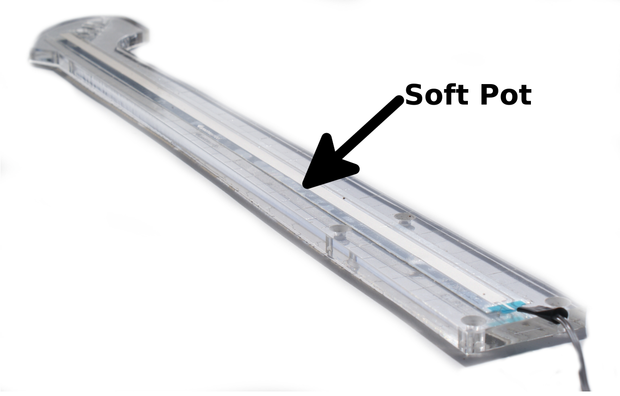

Figure 6. First neck prototype for the BLADEAXE based on a soft pot.

4.3.2 Simple Buttons Based Prototypes

Most of the commercial guitar MIDI controllers have button based necks: the starrlabs guitars, [13] Yamaha's EZ-AG [14], incidents' *gtar*, [15] etc.

Buttons have many advantages: they are very cheap, reliable and they provide haptic feedback to the performer when they are engaged which is a very important feature. Indeed, we found out that it is very hard to know if the pitch of the string is changed properly without getting a physical feedback which discouraged us from building a neck based on capacitive touch sensors.

We considered using pressure sensitive buttons (that are much more expensive than discrete buttons) but we realized that these wouldn't improve the control a lot. Yet, we wanted the performer to be able to bend the pitch of the strings and add vibrato. Therefore, we added a pressure sensor placed between two silicon sheets at the bottom of the neck (see Figure 2) to detect the amount of force applied by the player to the buttons when pressing them.

The pressure sensor can also be used to control other parameters like an audio effect or to add artificial vibrato to the strings (in this case, we control the amplitude of the vibrato by pushing harder on the neck).

Our button system is based on six parallel rows of fourteen push buttons. We decided that fourteen semitones per strings (7/6 octave) was enough to play a big part of the electric guitar repertoire. Unlike on a real neck, buttons are equally spaced. Indeed this enabled us to greatly simplify the design (we didn't have to use a custom PCB) and we thought that guitar players should be able to adapt to a "linear" neck. Moreover, most commercial MIDI guitars have equally spaced buttons.

On the electronic side, each row of buttons representing a string acts as a voltage divider. Each button outputs a different voltage that is measured on one of the analog inputs of the Arduino (see Figure 1). Priority is given to the lowest buttons in order to enable the player to do "hammer-ons" or to play bar-chords.

We spent a lot of time trying different kinds of buttons. Our first design was based on a silicon sheet that we placed over the electronic push buttons (see Figure 7 for the silicon buttons and Figure 10 for the electronic buttons board). The texture of silicon was very nice because it felt a little bit like skin. However, this solution presented many drawbacks. For example pushing very hard on a button could sometimes trigger neighboring buttons because of mechanical coupling. Another big issue with this design was that it was very hard to do slides. Finally, our silicon buttons were a little bit too sensitive and it was hard in the case of some chords to know if a finger was touching the string or not.

Figure 7. BLADEAXE neck based on silicon buttons. Buttons were 1/8" high.

Despite the fact that we really liked the idea of having silicon buttons, we decided to adopt a more robust and durable solution based on laser-cut acrylic buttons. These worked in a way similar to the silicon one by placing them above the electronic push-buttons board in order to reuse it (see Figure 8). While these acrylic buttons worked much

[12] https://www.sparkfun.com/products/8681.
[13] http://www.starrlabs.com/
[14] http://usa.yamaha.com/products/musical-instruments/entertainment/lighted_key_fret_instruments/ez_series/ez-ag/.
[15] http://www.gtar.fm/

better it was still relatively hard to slide between them because of their square shape. We also found that it was difficult to distinguish them because they all had the same color. This is what led us to the final version of the BLADEAXE neck.

Figure 8. First version of the BLADEAXE laser cut acrylic buttons.

4.4 The BLADEAXE Neck

The final version of the BLADEAXE neck is very similar to the one described in the last paragraph of the previous section. Buttons have a round shape in order to allow players to slide their fingers along "virtual strings". Each fret has a different color to easily distinguish it. Of course, the pressure sensor is still present at the bottom of the neck and can be used to add more expressivity to the play.

Very thin capacitive touch sensors were added at the top of each button in order to detect if the performer is touching the button without pressing it. In this case, the physical model switches to a "harmonic mode", just like on a "real" guitar when a string is touched but not pushed against a fret.

This final version of the neck uses seven analog inputs on the Arduino Due: six for the strings and one for the pressure sensor.

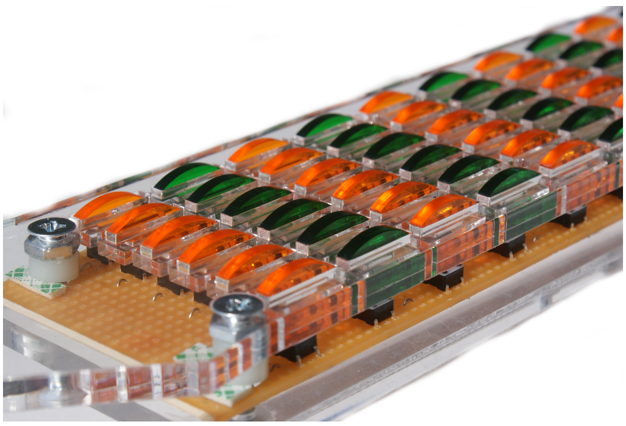

Figure 9. Laser cut acrylic buttons as they appear in the final version of the BLADEAXE neck.

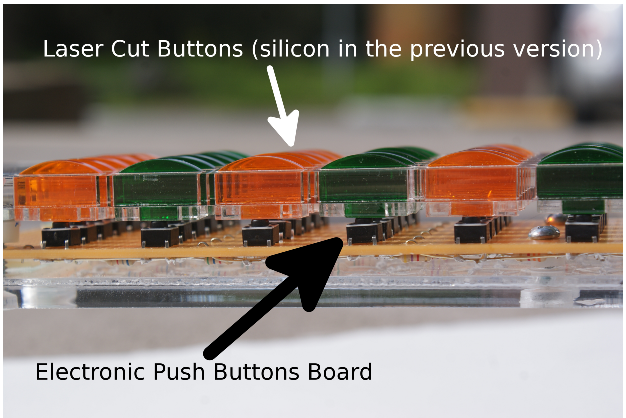

Figure 10. Electronic push-buttons fret board with laser-cut acrylic buttons over them as they appear in the final version of the BLADEAXE neck. The same electronic push-buttons fret board was used for the silicon and the first laser-cut acrylic buttons versions of the neck.

5. CONCLUSION

The BLADEAXE offers a level of interactivity with physical models that has rarely been achieved in the past. The plucking system for "the right hand" prove to be very reliable and provide a very high quality expressive controller for exciting virtual strings. The neck allows playing simple tunes as well as most standard guitar chords. However it could still be improved in many ways. For example, we'd like to make the buttons a little bit longer to facilitate the play of some chords that require the fingers to be very close to each other. We also would like to use better electronic buttons to make the neck more responsive. Finally, we unsuccessfully tried to use an embedded Linux *UDOO* [16] board to compute the sound of the physical model to make the BLADEAXE a fully standalone instrument. We didn't give up on this idea and we might try a different solution that would imply the use of a *FPGA* [17] board like *Digilent Inc. Altys.* [18] We might also try to solve the issue we had on the *UDOO* board which was related to the kernel of the Linux distribution it is using (*Linaro Ubuntu*).

Currently, we spent most of our time trying to make an electronic guitar that would be as close as possible to its real counterpart. This is obviously not an end in itself as a digital guitar has much more to offer in terms of sound and interaction than a "real" one. A simple example is that the BLADEAXE has a "chord mode" where one button on the neck corresponds to one chord which is very convenient for people who don't know how to play guitar. We can also think about new sound effects that could originate directly from the string itself unlike current effects that are only based on the processing of the sound created by the strings. Moreover, we can think about the use of more esoteric sensors to control the pitch of the virtual strings to add a new level of interactivity to the guitar performance: accelerometers, distance sensors, etc.

[16] `http://udoo.org/`
[17] *Field-Programmable Gate Array*
[18] `http://www.digilentinc.com`

We believe that hybrid instruments based on physical models have a lot to offer. They provide a very high level of interactivity and expressivity that other digital instruments often miss. In addition to implementing the different improvements mentioned previously on the BLADEAXE, our plan is to build other instruments based on the same techniques like a percussion instrument. Finally, we also started working on a virtual violin that uses the same polycarbonate excitation system as the one used in the BLADEAXE.

6. REFERENCES

[1] J. O. Smith III, *Physical Audio Signal Processing*. https://ccrma.stanford.edu/~jos/pasp/, Dec. 2010, W3K Publishing, online book.

[2] E. Maestre, *Modeling Instrumental Gestures : an Analysis/Synthesis Framework for Violin Bowing*. Ph.D. Thesis – Pompeu Fabra University (Barcelona), 2009.

[3] T. Meurisse, A. Mamou-Mani, and R. Causse, "Simulations of modal active control applied to the self-sustained oscillations of the clarinet," in *Proc. of SMAC/SMC*, Stockholm (Sweden), 2013, pp. 211–215.

[4] M. Puckette, "Playing a virtual drum from a real one," *J. of the Acoustical Society of America*, vol. 4, no. 130, pp. 2432–2436, 2011.

[5] S. Serafin, N. Bottcher, M. A. Cruz, A. Fredslund, S. Gelineck, C. L. Lorensen, G. Talaganov, and P. Pozza, "Novel interfaces for controlling sound effects and physical models," in *Proc. of the 1st Nordic Music Technology Conference*, Trondheim (Norway), 2006, pp. 145–151.

[6] E. Berdhal, *Applications of Feedback Control to Musical Instrument Design*. Ph.D. Thesis – Stanford University (USA), 2009.

[7] D. Schlessinger and J. Smith, "The Kalichord: A physically modeled electro-acoustic plucked string instrument," in *Proc. of the International Conference on New Interfaces for Musical Expression (NIME)*, Pittsburgh (USA), 2009, pp. 98–101.

[8] K. Karplus and A. Strong, "Digital synthesis of plucked string and drum timbres," *Computer Music Journal*, vol. 7, no. 2, pp. 43–55, 1983.

[9] D. A. Jaffe and J. O. Smith III, "Extensions of the Karplus-Strong plucked string algorithm," *Computer Music Journal*, vol. 7, no. 2, pp. 56–69, 1983.

[10] J. Smith, "Virtual electric guitars and effects using Faustu and Octave," in *Proc. of the Linux Audio Conference*, KHM – Cologne (Germany), 2008, pp. 123–127.

[11] N. Fletcher and T. Rossing, *The Physics of Musical Instruments*. Springer, 2005.

[12] L. Kessousand, J. Castet, and D. Arfib, "'gxtar', an interface using guitar techniques," in *Proc. of the International Conference on New Interfaces for Musical Expression (NIME)*, Paris (France), 2006, pp. 192–168.

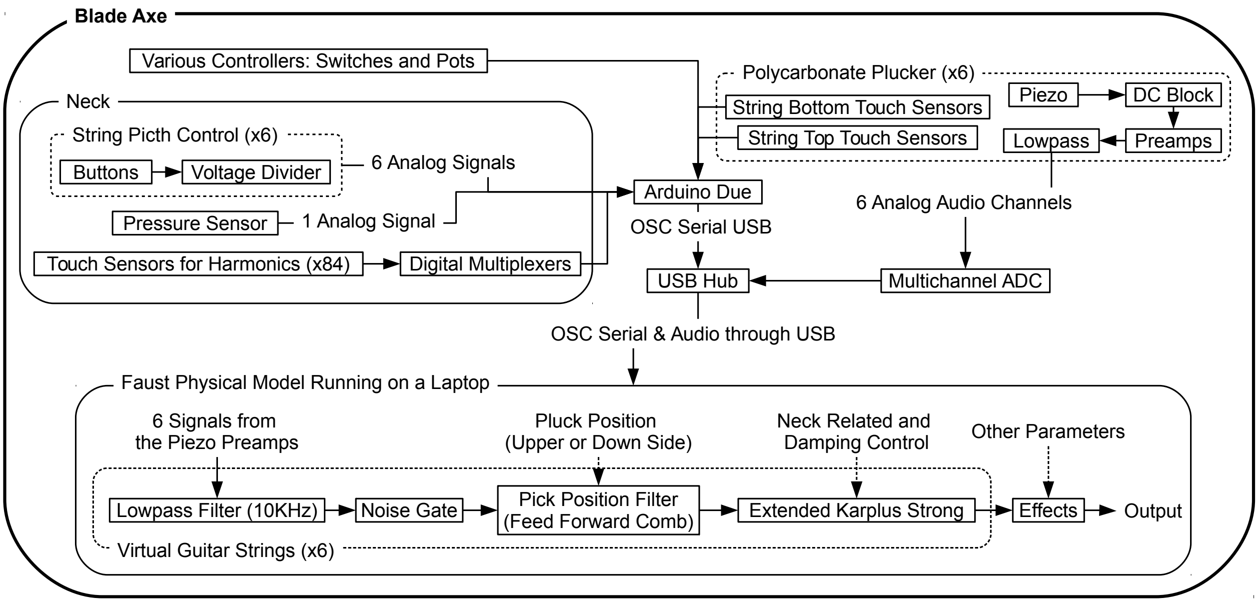

Figure 1. Overview of the different components of the BLADEAXE.

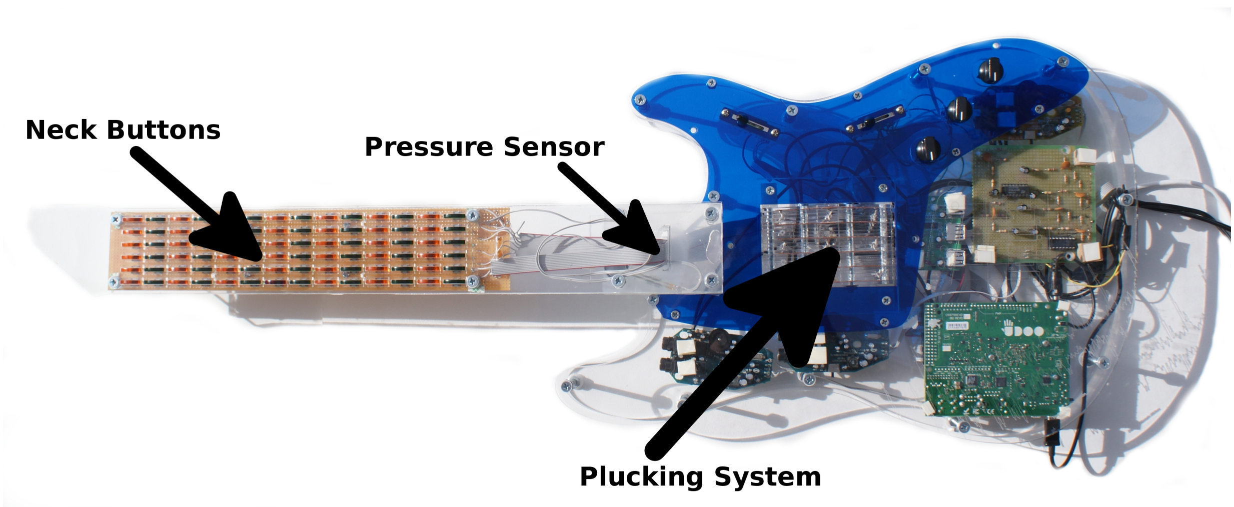

Figure 2. Top view of the BLADEAXE.