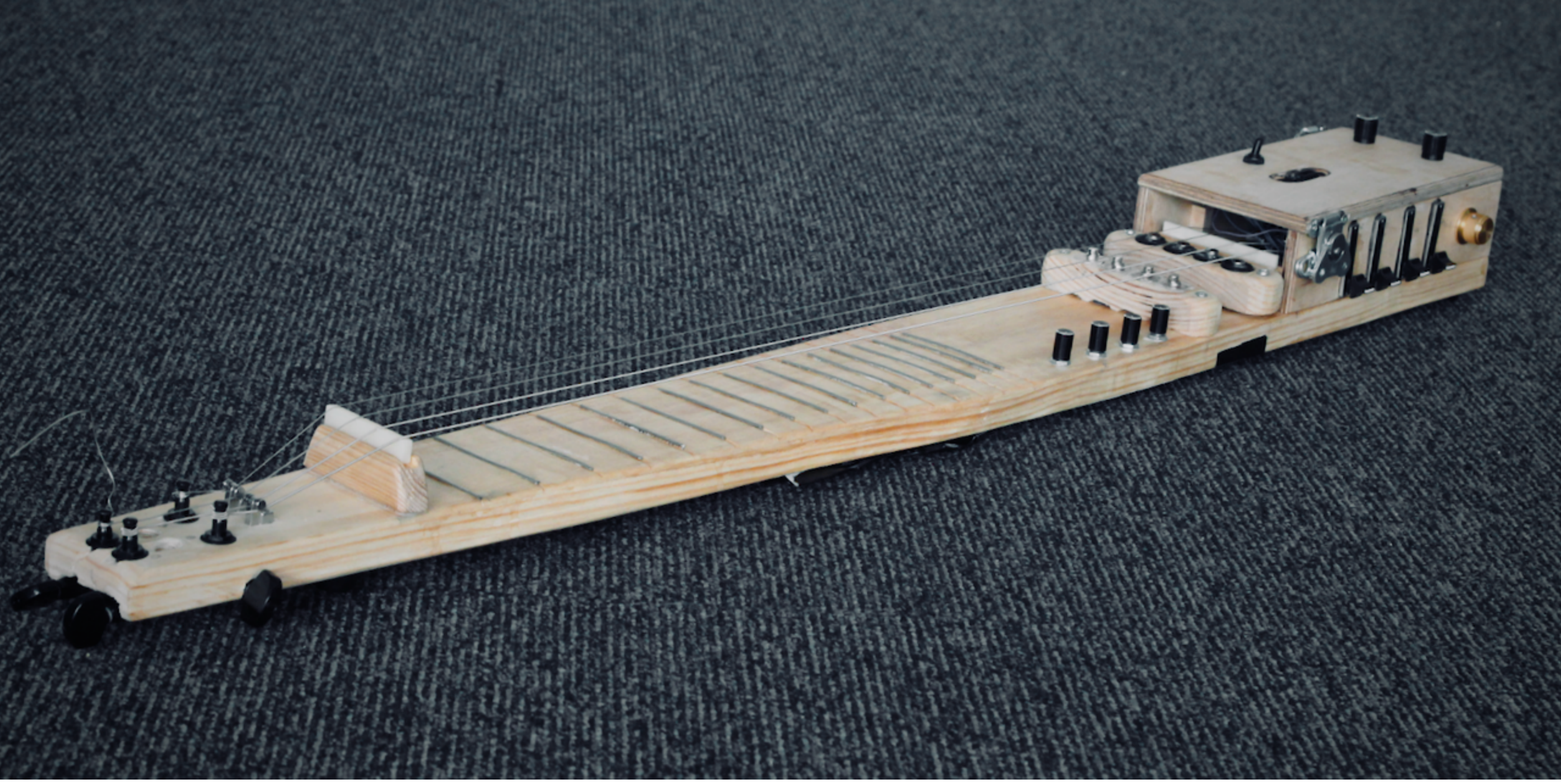

Slide guitar instrument with DSP processing

Steffen Jan Körper

Sound and Music Computing

Master's Project

STUDENT REPORT

AALBORG UNIVERSITY

The 'Uhane Wave Slide

New Interface for Musical Expression

Steffen Jan Körper

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May 2023

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STUDENT REPORT

The Technical Faculty of IT and Design
Department of Architecture, Design and Media Technology
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Abstract:

With the 'Uhane Wave Slide, a new digital musical instrument has been created that is based on the playing principle of a lap steel guitar, but expands and modifies it. The instrument has an electric circuit and through the feedback of magnetic fields its strings can be made to vibrate permanently without striking them. The string vibration recorded with a piezo bridge pickup is analysed in a Bela microcontroller in real-time and the frequency and the course of the amplitude are continuously determined. Two sound generators are available to the user, which can be individually mixed with the output signal and transposed octave by octave with the help of various faders. For playful interaction, the instrument has potentiometer-controlled filters and effects as well as an infrared distance sensor with which the master output volume can be played without contact, similar to a theremin.

AALBORG UNIVERSITET
STUDENTERRAPPORT

Det tekniske fakultet for IT og design
Institut for Arkitektur, Design og Medieteknologi
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Abstract:

Med 'Uhane Wave Slide er der skabt et nyt digitalt musikinstrument, der er baseret på spilleprincippet fra en lap steel guitar, men som udvider og ændrer det. Instrumentet har et elektrisk kredsløb, og ved hjælp af tilbagekobling af magnetfelter kan strengene bringes til at vibrere permanent uden at slå på dem. Strengenes vibrationer, der registreres med en piezo-bro-pickup, analyseres i realtid i en Bela-mikrocontroller, og frekvensen og amplitudeforløbet bestemmes løbende. Brugeren har to lydgeneratorer til rådighed, som kan blandes individuelt med udgangssignalet og transponeres oktav for oktav ved hjælp af forskellige fadere. Til legende interaktion har instrumentet potentiometerstyrede filtre og effekter samt en infrarød afstandssensor, hvormed masteroutput-volumen kan spilles berøringsfrit, svarende til en theremin.

Statement of authorship

“I hereby confirm that I wrote this master’s thesis on my own and I did not use any other aids or sources, except those indicated. I furthermore confirm that I did not submit the thesis as assessed course work elsewhere nor it was published in Danish or any other language.”

The author has objections to making the present master’s thesis available to the public.

Aalborg University, May 25, 2023

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Contents

About the structure of this work:

In this thesis, a digital musical instrument (DMI), the 'Uhane Wave Slide was created. On the way from the first design idea to the evaluation of the finished instrument, numerous methods and procedures, e.g. for contact-free excitation of the strings, were developed and compared with each other. From this pool of ideas and procedures, the variants that seemed most effective for the intended design goal were selected in the course of the development process. Some of the techniques developed and tested in the prototype status are thus no longer included in the final design of the instrument. Accordingly, this paper has been divided into two parts. Part 1 - the main document - contains only the techniques used in the final instrument and can thus be regarded as a complete and final technical documentation of the created instrument. Part 2 - the appendix - documents the techniques that go beyond the final design draft and have been developed and tested in the prototype construction. The documentation in the appendix is intended to serve interested parties and subsequent instrument makers to learn about alternative procedures and understand their advantages and disadvantages compared to other techniques.

Chapter 1

Introduction

1.1 History of Musical Instrument Making

Traditionally, musical instrument making can be located in specialised crafts. The families of instruments known to us have existed in their present form for many centuries. The piano in its present form, for example, was developed in the 18th century [46] and has not been fundamentally changed or further developed since. Although the first trumpet-like instruments probably existed as early as 3,500 years ago, the trumpet with a rotary valve that we know of was probably given its final form in 1832 by Joseph Riedl in Vienna [49]. Technical changes to these traditional families of instruments thus usually represent small further developments of the always-same functional principle, usually aimed at better playability, a higher degree of precision and control when playing, further development of the timbre or greater simplification in the manufacturing process. This traditional and slow development in musical instrument making of course always had a coupling with performance practice and teaching in the field of music. Some musical genres can be strongly defined by the musical instruments used for them, there are classical instrumentations for orchestras and a certain limited number of instruments are offered for learning at schools and universities.

Due to the development of technical possibilities, especially electronic and computer-aided processes, musical instrument making has changed a lot in the last century and especially in the last decades. New recording systems such as magnetic pick-ups and the possibility of electric amplification have helped the electric guitar gain worldwide recognition and popularity since 1920 and have given rise to new musical genres such as rock music. Worth mentioning in the development of robotised self-playing instruments is the album "Orchestrion" by jazz guitarist Pat Metheny from 2010 [38], where an entire orchestra was replaced by robotised instruments. Through electroacoustic and computer-based processes, instruments no longer need to have the traditional sound body nor traditional excitation mechanisms. With sensor-based solutions, sound-generating processes can be started and controlled by gestures, or touch, allowing new forms of interaction. The number of technical developments in the field of musical instruments has increased exponentially since then. Musicians and artists have created new music with specially designed and built instruments, and sensor-controlled sound creation processes have become part of performative performances and interactive exhibitions. An internationally networked specialist community for New Interfaces for Musical Expression (NIME), which began as a workshop in Seattle in 2001, has set itself the task of researching aspects of musical instrument construction.

1.2 Design process in DMI making

The question of "how-to-design" is a much-noticed, sometimes humorous, always passionately discussed topic within the field of Human Computer Interaction (HCI) and digital music instrument (DMI) making, e.g. [11], [45], [36]. As the traditional forms of musical instrument making seem to be dissolving, design processes are becoming much more significant. Design can be playful or taken very seriously. Throughout history, design has often been very successful when it has been able to break free from cultural and preconceived categories and grow beyond existing forms. This de-conditioning in DMI design is a big part of the work of Lepri et al. who investigates cultural imprints [23]. Lepri also was the main organiser of the 10,000 instruments workshop at NIME conference 2022 [24] where participants were asked to design as many NIMEs as possible in a short time.

Because the design process is so important, co-design or participatory design approaches involving stakeholders in the musical instrument industry and potential users such as professional musicians are becoming more common in the field.

The university process of a Master's thesis - in the context of which the present NIME was developed - requires a complete description of the task to be available and contractually recorded at the start. Adjustments along the way are not excluded, but the basic concept and design should already be established at the beginning. Co-design processes have therefore been difficult to implement in the context of this work. Instead, the design idea was based on a pool of previous experience. Projects in the study subject "Modelling Physical Systems" tought by Stefania Serafin and "New Interfaces for Musical Expression" taught by Daniel Overholt in my studies at Aalborg University [42], as my first self-made instruments gave me first experiences and already somewhat prepared the way for the design idea of my master thesis. As a long-time guitar player and hobby musician, I was also able to incorporate my own experience in dealing with musical instruments into the concept. Nevertheless, at the start of the Master's thesis, intensive brainstorming was carried out and about 30 different free drawings were made and team meetings were held with my supervisor Daniel Overholt, before the idea was determinated.

As music instrument craft always serves music playing, skills and expression of nuances in performance, play a big role in DMI-making. The time it takes to learn and master an instrument is exemplified for four instruments in figure 1.1.

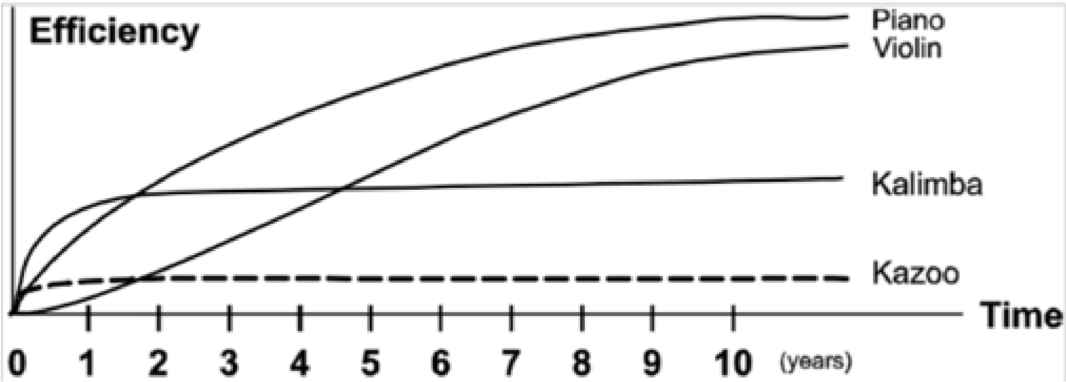

Figure 1.1: Approximate learning curve for the (a) kazoo, (b) kalimba, (c) piano and (d) violin, within a period of 10 years according to [17]

When hands are used for interaction, richness and expressiveness often go together with the technical solution for tangibility of a DMI [16], [2]. Other well-known design challenges for DMI are live music situations in which listeners no longer understand what the musician is doing and thus lose connectivity to the performance. Embodiment and performative aspects must therefore be considered right from the start. Also e.g. tactile, kinesthetic and visual feedbacks had been seen as crucial for performance control [21]. According to [3] "The finer the musician, the smaller the details". [28] states that design and creativity must not one-sided be driven by technical development, but negotiated until the knowledge about technical solutions supports creative ideas. Finally, there are limits that can't be overcome imposed by the available technology, as e. g. latency.

In my design, it is important to me to take up, change and use an already existing way of interaction. On the one hand, this gives already experienced musicians the opportunity to use and adapt their technical skills - the new musical instrument does not have to be learned completely from scratch. On the other hand, the tradition of musical instrument making is respected. No completely new instruments or families are created, but the design drafts for new musical instruments fit into already existing musical families and, if necessary, extend them. In the language of the NIME community, this approach could possibly be called an "augmented instrument". In this project, my aim was to use and develop the established technique of playing a slide guitar as a fretless instrument. Compared to conventional slide guitars, the instrument created in this master's thesis has numerous extensions and changes in the sound generation process that allow new ways of interaction. The aim was to change the haptic feeling and feedback that a player has when playing. The aim was also to make the instrument sound different from conventional slide guitars, to create new forms of interaction as well as a new interpretation of the instrument. Out came a hybrid instrument with analogue sound production, mechanical excitation and digital sound processing The design was developed step by step from the first idea to the finished DMI and continuously adapted. An important step was the experimentation, testing and comparison of different excitation methods for the strings and a constant revision of the digital sound generation process based on the developed interaction possibilities.

1.3 Linking to other DMI designs and commercial products

Since so many different musical instruments have been designed in the last decades, it cannot be excluded that a similar approach has already been developed somewhere in the world. In-depth research during the design process has revealed numerous other projects that share similarities with the design approach discussed here. These are for example:

- Jeff Snider's Electrosteel [39]
- Robotic Guitar Instrument of Leigh et al. [22]
- The Langspil from Armitage et al. [4]
- DVINA a electro-acoustic instrument from SOMA [40]
- The Magnet resonator piano of McPherson [27]
- Robotically Augmented Electric Guitar for Shared Control [29]
- Cyther: A human-playable, self-tuning robotic zither of Barton et al. [7]
- Tremolo-Harp: A Vibration-Motor Actuated Robotic String Instrument of Kemper [20]

None of these musical instruments is completely identical to the design developed in this thesis. The present design is different or new in particular because it uses magnetic fields to create a contact-free vibration of the strings for the sound generation process combined with digital sound replacement. This chosen technique allows an infinite sustain of the sound of the string and an individual sound shaping.

When a string vibrates on a conventional instrument, the vibration is reduced over time by damping mechanisms until it stops. These damping mechanisms cannot be completely avoided physically. Through technically precise adjustment of the guitar, guitar manufacturers try to keep the damping of strings low. Sustain is therefore sometimes regarded in guitarist circles as a quality feature in guitar construction. Sustain is also produced playfully by various playing techniques, such as light vibrato. Technically, extending sustain on electric guitars, for example, can be achieved by inducing vibrations into the vibrating string. Inducing vibrations into a string can basically be done in two different ways - touched or untouched. Touching the string would be equivalent to repeated mechanical excitation, such as in robotic stringed instruments. Touch-based excitation of an already vibrating string has the consequence that at the moment of contact of the string, the existing vibration is first completely damped and then the string is correspondingly mechanically steered out of the rest position again, in order to vibrate again periodically around its own rest position when released. In the context of the present work, only the non-contact possibilities for extending the sustain are examined, which make use of the movement of the already vibrating string and amplify it. Various commercial solutions and products attempt to technically extend the sustain of guitars. The principle of endless sustain extension is therefore not completely new, but is already available in modified form in products available on the market.

- A patent for a version of an magnetic sustainer by Osborne and Hoover [31].
- Sustaniac - An electromagnetic sustain system that can be installed into many electric guitar control cavities from Maniac Music Inc. [43].
- HD Susttainer Installation Kit for on-board electric guitar sustainer from Hard Driver[12]

Within the scope of this project, newsletters of the companies have been joined, discussions in online forums about the performance of the products and the public available information have been studied, to understand their main working principles, advantages and disadvantages. It unfortunately wasn't possible to get access and test and compare the products withing this master thesis. Another product of non-contact excitation that is worth highlighting and essential in relation to this work is the EBow [32]. Access to the Ebow was given in the "Manufakturet" Laboratory at Aalborg University, therefor first testings of touch-free sustain and excitation of strings could have been done with the Ebow product. More DIY methods of creative ideas for contactless sustain extension can be found in the "hobbyist" sector on youtube [26]

It can be summarized, that there are examples that use principles based on code-based computer control, e.g. using pulsewidth modulation to control the rotation speed of motors, as well as principles of purely anaolgic circuits that manage without computer-based control. The approaches that had been found in the literature research and that could be tried out In the context of this work are documented in Appendix A. The principle used in the final realisation of the instrument in this thesis is based on the principle of EBow.

The EBow technique, its modification and implementation will therefore be discussed in more detail in section 2.3.2.

Another component that plays an important role in the developed design is the automated pitch detection. Since the instrument was designed as a hybrid between analogue sound generation and digital sound processing, a core element, the pitch detection of the analogue process, is used to control the digital sound replacement. There are already products and technical realisations based on this principle commercially available. For example, there are attachments for guitars that translate what is played into the digital MIDI protocol.

- TriplePlay a MIDI Guitar Controller and Software from Fishman [14]
- Expressiv Midi Pro 2, a MIDI Guitar from Rob o Reilly [33]

Further examples are given in the appendix A. The pitch detection technique used in this thesis is referred to in more detail in section 3.2.

Chapter 2

Technical Basics - Hardware

2.1 Acoustic processes in string instruments

Stringed instruments have been around for thousands of years. The principle is simple: by striking, plucking or bowing, a taut string consisting of hair or thread is set in vibration. The oldest depictions of a musical bow can be found on 13,000-year-old cave drawings [47].

Usually a string is fixed at both ends and can vibrate freely between these fixed points. The pitch of the vibration of a string is therefore not dependent on the type and manner of excitation, but on the mechanical vibration properties and the suspension of the string and thus essentially on its length. As in most string instruments all strings have the same length, yet they vibrate at different frequencies. Influencing factors on the frequency with which a string vibrates are material properties as well as the tension with which the string is clamped between the fixing points. The following physical relationship summarises the fundamental frequency of vibration of a string:

$$f = \frac{\sqrt{(\frac{\psi}{\pi \cdot \rho})}}{d \cdot l} \tag{2.1}$$

f = Frequency in Hz
ψ = String tension in Newton (N)
d = Diameter in m
ρ = Density in kg/m^3
l = String length in m

In addition to a vibration in the basic frequency pattern, more complex vibrations can also occur along a string. Fig. 2.1 shows the manifestations of various vibration patterns as a result of the excitation of a string in the form of partial vibrations. These vibration patterns are usually in a harmonic relationship to the fundamental vibration and result in the distinctive sound of a string in the form of so-called harmonic overtone series.

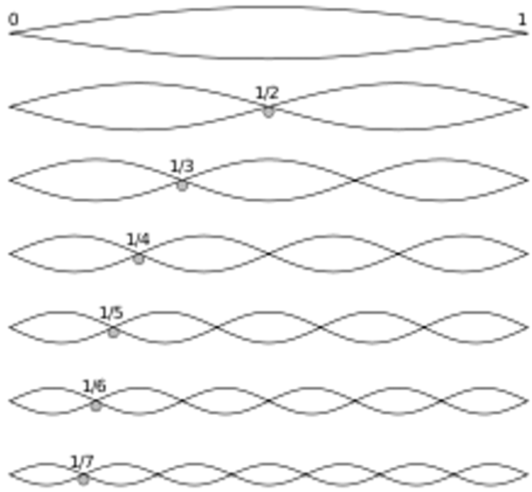

Figure 2.1: Formation of different vibration modes in one string after [48]

When a string vibrates, it also causes surrounding air particles to vibrate. These vibrations can be perceived as sound by the ear. However, a string is comparatively thin and causes only a few surrounding air molecules to vibrate. The resulting tone is correspondingly quiet. For this reason, resonators are often used in the construction of stringed instruments. The string is connected to a vibrating plate or body via a bridge. The vibrations induced by the string in the instrument body are distributed in the instrument depending on the material properties of the instrument body and are transmitted to the surrounding air in the form of surface waves. The instrument body can amplify or damp frequency components accordingly. Thus, the instrument body also has an essential part in the sound of a traditional instrument.

2.2 Electro-acoustic conversion in string instruments

If it is desired to amplify the sound of an acoustic stringed instrument not purely via the instrument body, but especially electrically, it is possible to record the sound waves transmitted from the instrument body to the air with a microphone. Depending on the use and quality of the microphone, this approach enables a particularly natural sound reproduction for acoustic instruments. In electric guitar construction, on the other hand, large or hollow instrument bodies are not usually used. The amplification and sound deformation properties of a solid electric guitar wood body are low compared to those of an acoustic guitar. An electric guitar therefore sounds correspondingly much quieter than an acoustic guitar without electrical amplification, and even with a microphone recording it is not particularly rich or beautiful in sound. In electric guitar construction, therefore, magnetic pickups are often used to capture the string vibration. These pickups, made of wound coils, give the electric guitar its characteristic sound. The electric guitar strings, unlike strings of an acoustic guitar, consist of a magnetisable metal that induces a voltage in the pickup coil. Alternatively, piezo-electric pickups, can be applied or inserted directly onto the surface of the instrument or, for example, under the bridge of an instrument. The electro-piezo conversion principle consists of a direct conversion of surface structure-borne sound waves into electrical signals. Piezo pickups are more often used in acoustic or semi acoustic instruments, such as double bass, acoustic guitar, cello, violin, where it is desired to amplify the signals electrically without using a microphone when playing.

2.3 Electro-acoustic circuits

Alongside DSP-based solutions, analogue electronic circuits are ubiquitous in audio signal technology. For understanding of the in this project implemented circuits it is necessary to understand the working principles of some electronic components in AC circuits.

2.3.1 Analogue signal circuits

A current-carrying conductor generates a magnetic field. If an electrical conductor with many turns is wound around a core in the form of a coil, these fields of the neighbouring conductors overlap and increase the field strength. If a magnetisable object is moved in this magnetic field, a voltage is induced in the conductor. Conversely, however, a change in the current in the conductor is also capable of causing a change in the magnetic field and thus possibly moving a magnetisable object in the magnetic field. These principles are used in most inductive processes and are an important part of motors and electromagnets.

The inductance of a coil can be calculated with equation 2.2. It is thus highly dependent on the winding, the wire used and the core material.

$$L = n^2 \cdot A \cdot \mu_r \cdot \frac{1}{l} \tag{2.2}$$

L = Inductance in Henry (H)
n = Number of turns
A = Coil cross-sectional area in m^2
μ_r = Material constant for core, e.g iron = 300 - 10000
l = Coil length in m

The magnetic field generated by a coil does not only act outwards. One speaks of self-induction when a changing magnetic field of a conductor has an influence on the current in the conductor itself. In the AC field, the impedance generates a reactance that, together with the ohmic resistance of the conductor, determines the current flow through the coil. The reactance of a coil in an AC circuit is frequency-dependent. The higher the frequency, the higher the reactance of a coil as shown in equation 2.3.

$$X_L = \omega \cdot L \tag{2.3}$$

X_L = Reactance in Ω
$\omega = 2\pi \cdot f$

Capacitors behave in the opposite way to coils in the alternating current circuit. Here, too, a frequency-dependent reactance is formed, but the frequency dependence is reversed compared to the coil. The higher the frequency, the lower the reactance and the more permeable the capacitor. The capacitance of a capacitor can be calculated as shown in equation 2.4.

$$X_C = \frac{1}{\omega \cdot C} \tag{2.4}$$

X_L = Reactance in Ω
C = Capacity in Farad F
$\omega = 2\pi \cdot f$

Looking at these relationships, it is relatively easy to see that these electrical components can be used as signal filters. But more than that, the coil and capacitor together act as an oscillator. In a coil voltage and current are not in phase. In a perfect coil, the voltage precedes the current by 90°. In an ideal capacitor, however, the current precedes the voltage by 90°. In the so-called oscillating circuit, the condenser discharges while the coil charges. Then the coil begins to discharge and the condenser is charged. In an ideal oscillating circuit without losses, this movement of electric charge in a certain component-specific frequency could continue indefinitely without power input. The freuqncy of this oscilaating behavior can be calculated as shown in equation 2.5, also known as the Thomson's formula.

$$f = \frac{1}{2\pi \cdot \sqrt{LC}} \tag{2.5}$$

2.3.2 The Ebow circuit

An EBow is a device that is held with one hand over the strings of an electric guitar and stimulates this string to vibrate without physical contact that it can sound endlessly without being struck. If an EBow is brought close to a magnetic guitar pickup, not only is the string excited to vibrate, but the magnetic waves of the EBow coils are additionally transmitted directly into the pickup coil. The sound of the changing magnetic field in the EBow is thus made directly audible without taking the diversions via the vibration of the string. Consequently, the sound result of the EBow varies greatly depending on the area of the guitar in which it is used. The EBow was invented and patented in 1969 by Greg Heet and has been marketed since the 1970s by Heet Sound Products, in Los Angeles, California [32]. Today, however, devices similar to the EBow are commercially available from various manufacturers, like the Aeon from TC Electronic [13] or the JGE-01 from Joyo [18].

The EBow represents a niche product and although it is unknown to many musicians and even guitarists, the list of artists who used the EBow in professional productions is long. Internet forums discuss a list of names that includes, for example, Pearl Jam, Soundgarden, John Petrucci, Metallica, Coldplay and Radiohead [19]. The working principle of the EBow can be described in a simplified way as follows: A coil with a high inductance, serves as a reciever of the string vibration in the magnetic field. This induced alternating current is amplified in the circuit. The amplified signal is conducted to a sender or transmitter coil, which has a low inductance. If an alternating current is introduced into the transmitter coil, the magnetic field changes accordingly and this causes a force on the electric guitar string located in the magnetic field and thus stimulates it to vibrate or to sustain vibration. Due to the direct coupling between the input signal at the receiver coil and the output signal at the transmitter coil, the change of the magnetic field at the transmitter coil follows the vibration of the string. This creates a technically supported feedback loop in which the string keeps itself oscillating.

In addition to this direct correlation between input signal and output signal, the amplified output signal is also fed back to the input of the amplifier as electric feedback and added to the signal of the input coil. A resistor regulates the ratio between the feedback signal and the signal of the input coil. The additional feedback loop makes the EBow circuit more efficient. A 9 V battery is usually sufficient to operate an EBow for hours.

In addition to the coils, the circuit contains numerous capacitors, some of which act as filters, i.e. they are impermeable to certain signal components but also induce their own oscillations in connection with the coils. If the magnetic oscillation is made audible by bringing the EBow close to the magnetic pickup of a guitar, these natural oscillations are perceptible in the form of overtones. They give the EBow the characteristic sound of a bow sweeping over the sides.

The exact electrical circuitry of an EBow and the electronic components used are not publicly available. Outside of the manufacturer's company secret, the exact construction is not known. A request to the manufacturer to send the circuit was

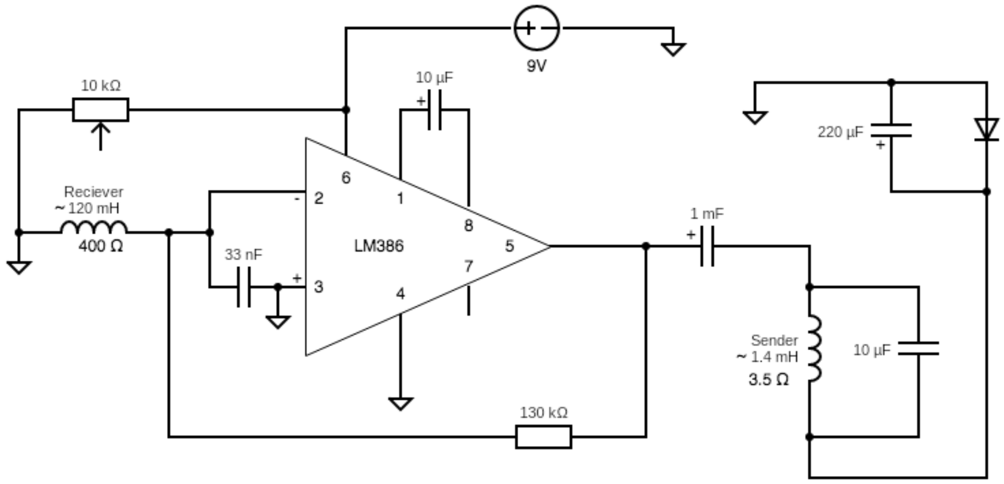

Figure 2.2: For this project adjusted circuit based on [44]

accordingly denied or remained unanswered in another case.

Numerous musicians, hobbyists and EBow enthusiasts have tried to rebuild the circuit of the EBow in the past and have partially disassembled original EBows for this purpose.

According to the research carried out, the most promising documentation can be found in [1] and a recently published series of videos by a Youtuber called "Vegas Cycling Freak" [44]. On the website of [44] you can find a circuit which, according to his author works and sounds like an EBow, but is not able to build up the same magnetic force as an EBow.

In the course of this work, a number of calculations and tests were carried out to find the best design case for the circuit. A main part of the tests was the optimisation of the impedances of the coils in interaction with the capacitors used. An overview of the components used in the tests can be found in Appendix A.

The tests showed that the vibration amplification achieved by the circuit as shown in Figure 2.2 was the greatest possible in the present project.

Further results of the experimental work with the EBow circuit are the discovery of numerous sound designs. As mentioned, the interplay of capacitors and coils influences the overtone content of the oscillation, but also the current and strength of the magnetic field. While experimenting with the electronic scarf circuit, I succeeded in developing many interesting and special sounds.

Since all the electronic components interact with each other, especially due to the feedback from the operational amplifier LM386 itself, it is difficult to precisely calculate and predict the influence of the individual components - and would have exceeded the scope of this paper by far. Nevertheless, it made sense to empirically combine different components and compare the output. Many sounds sound distorted, but in a nice and special way. This behavior might come from capacitors and coil connections, reacting as oscillating circuits, feeding high frequency vibrations into the circuit. The sounds vary from heavily distroted to somewhat nice and tingling top end, with interesting crackling.

Figures 2.3 to 2.6 show a few photographs of oscillations of the EBow circuit taken while measuring with the Oscilloscope. The upper yellow signal always shows the signal along the input coil having the string vibrating through the magnetic field itself. The green lower displayed signal always shows the transmission coil and has a about 20 times higher voltage than the signal at the input coil. Unfortunately, no audio recordings could have been made. An EBow is a hand-held device. The amplitude of the string vibration and the overtones can be easily controlled by moving the EBow closer to the strings and the guitar pickup. So the string will sound only when desired.

Figure 2.3: Example 1 of signal input and output forms as a result of testing different components in the circuit. The waveform of the output coil (green) shows a plateau form and spikes

In the present design, the EBow coils are permanently installed. The sounds induced by self-oscillation do not stop when the string is muted, for example, by placing a finger on it. The potentiometers are used to control the string vibration. To not limit the possibilities of playing the instrument too much, the oscillating circuits were designed to keep the self-oscillation noise as low as possible or to shift it into inaudible frequency ranges. The circuit was therefore adapted so that the resultant is primarily a pure fundamental in the form of a sine wave, without much noise, as shown in figure 2.5. This sine wave follows the note played on the string and does not add many overtones to the vibration.

Figure 2.4: Example 2 of signal input and output forms as a result of testing different components in the circuit. The waveform of the output coil (green) shows a shark fin like or saw tooth form

Figure 2.5: Example 3 of signal input and output forms as a result of testing different components in the circuit. The waveform of the output coil (green) resembles a sine wave oscillation

This is achieved, among other things, by means of "bypass capacitor filters" on the transmitter coil, see the 10 μF Capacitor in 2.2 along the sender coil) . Here, high-frequency components are filtered out by passing only the low frequencies to the coil. The high frequencies pass through the low resistance/impedance of the capacitor without passing through the coil. The filter also causes the total current at the coil to drop.

In a later design draft and finally the final design, I switched from pickup coils to a piezo pickup to pick up the string sound. This reduces the problem of undesired and directly induced magnetic self-oscillation even more.

Figure 2.6: Example 4 of signal input and output forms as a result of testing different components in the circuit. Here the waveform looks like a shark fin with high spikes

For sound control, a potentiometer was added to the circuit. The potentiometer on the receiver coil allows a certain amount of control by acting as a bypass resistor. Depending on the position of the potentiometer, certain frequency components are conducted more or less well through the coil. This also changes the timbre of the sound.

Chapter 3

Technical Basics - Software

3.1 SignalAnalysis with Fastforier-Transformation

According to Fourier, every oscillation, no matter how complex, can be represented as a sum of pure sine oscillations. The breakdown of complex oscillations into their components can be carried out with the Fourier transform. The Discrete Fourier Transform (DTFT) as shown in equation 3.1 is therefore a common technique in audio technology for analysing the frequency components of an audio signal.

$$X(\omega) = \sum_{n=-\infty}^{\infty} x(n)e^{-j\omega n} \tag{3.1}$$

In practical audio applications, it is common to divide an audio signal into different parts (buffers) with a length of the power of two in order to obtain information about the temporal change of the frequency components. The buffer length used have an influence on the quality of the Fourier transformation or fast Fourier transform (FFT). The frequency resolution of a FFT is always proportional to the number of samples in the buffer. The longer the sample buffer, the better the frequency resolution. The smaller the number of samples in the buffer, the worse the frequency resolution, but the better the time resolution. In connection with FFT, we often speak about the compromise between temporal resolution and frequency resolution. To avoid artefacts in the transition of signals from one sample buffer to the next, e.g. by cutting off incomplete periods of oscillations, the sample buffers are often multiplied by a window before the FFT that reduces the signal strength towards the sides.

$$X_N(\omega) = \frac{1}{2\pi}\int_{-\pi}^{\pi} W(v)X(\omega - v)dv \tag{3.2}$$

In order not to lose any information through windowing, overlapping samples are often used in the Fourier transformation of audio signals. But the window function itself also influences the quality of the FFT and leads to sideslopes in the frequency domain. As a good compromise between slope width and sideslope distance, among others the Hamming Window shown in equation 3.3 has become established in audio technology.

$$x(n) = \begin{cases} 0.54 - 0.46\cos\left(\frac{2\pi n}{N-1}\right) & 0 \leq n \leq N-1 \\ 0 & \text{otherwise} \end{cases} \tag{3.3}$$

Through the inverse FFT, a signal in the frequency domain can be converted back into a complex oscillation in the time domain as shown in equation 3.4

$$x(n) = \frac{1}{N} \sum_{n=0}^{N-1} X(n) e^{j2\pi \frac{n}{N}} \tag{3.4}$$

3.2 Rootnote detection with Harmonic Summation

Pitch is generally a perceptual component. What we perceive as pitch is a result of a certain frequency distribution. In the real world, we rarely encounter pure sinusoidal oscillations but always complex oscillations, possibly composed of sinusoidal oscillations which are multiples of each other, i.e. what we generally call harmonics. There are various methods for pitch detection, both in the time domain and in the frequency domain, which have different advantages and disadvantages. Harmonic summation (HS) is a method in the frequency domain. Compared to methods in the time domain, which are often based on autocorrelation or similar methods such as comb filtering, HS is computationally more expensive, but also leads to a more robust result for quiet signals or signals with a noise component. In the HS, the signal present in the frequency domain is iteratively shifted and added to itself and summed up. If the harmonic components of a periodic signal overlap during a shift, the summed output becomes as large as possible. The accuracy can be further increased by the Quadrature of the sum as shown in equation 3.5.

$$\hat{\omega_0} = \underset{\omega_0 \in [\omega_m in, \omega_m ax]}{argmax} \sum_{l=1}^{L} |X(\omega_0 l)|^2 \tag{3.5}$$

3.3 Harmonizer (Pitch Shift)

Multiplying each frequency component with a fixed value R in frequency domain as shown in equation 3.6 results in pitch shifting.

$$b_s(n) = R \cdot b_a(n) \tag{3.6}$$

The new bin with index k' is defined as

$$k' = floor(R \cdot k + 0.5) \tag{3.7}$$

To recalculate the phase of the new bins:

$$\phi_{rs}(n) = \frac{2\pi \cdot H(b_s(n) - k')}{N} \tag{3.8}$$

Then magnitude and phase can be reconverted to real and imaginary components

$$\phi_s(n) = wrap(\phi_s(n - H) + \phi_{rs}(n) + \frac{2\pi \cdot k' \cdot H}{N} \tag{3.9}$$

The interested reader is referred to [8].

3.4 Envelope Follower

Envelope following mainly works as lowpass filtering with two independent filter for rising period of a signal and the descening period of a signal. To design the filter-coefficients two values for attack and release τ_a and τ_r are used in equation 3.10 and 3.11

$$b_a = \sqrt[fs]{e^{\frac{-1}{\tau_a}}} \tag{3.10}$$

$$b_r = \sqrt[fs]{e^{\frac{-1}{\tau_r}}} \tag{3.11}$$

The envelope y(n) then can be calculated with:

$$y(n) = \begin{cases} b_a y(n-1) + (1 - b_a)x(n) & x(n) \geq n \geq y(n-1) \\ b_r y(n-1) + (1 - b_r)x(n) & x(n) < n < y(n-1) \end{cases} \tag{3.12}$$

3.5 Filtering

Linear-time-invariant (LTI) Filter are specified by the equation:

$$y(n) = \sum_{k=1}^{N} a_k y(n-k) + \sum_{k=0}^{M} b_k x(n-k) \tag{3.13}$$

3.6 Distortion

Distortion can be implemented as hard clipping or soft clipping. Hard clipping is characterised by an abrupt transition between unclipped and clipped areas of the waveform, resulting in sharp corners in the waveform. Soft clipping is characterised by a smooth approach to the clipping level, resulting in rounded corners at the peaks of the waveform. In the simplest and purest form of hard clipping, the input signal is simply clipped above a certain threshold, can be calculated as in equation 3.14.

$$y(n) = \begin{cases} -1 & x(n) \leq -1 \\ x(n) & -1 < x(n) < 1 \\ 1 & x(n) \geq 1 \end{cases} \tag{3.14}$$

In soft clipping, a signal is multiplied by a function. The equation 3.15in is an Example for soft clipping calculation.

$$y(n) = sgn(x) \cdot (1 - e^{-|x(n)|} \tag{3.15}$$

The interested reader is referred to [34]

Chapter 4

Hardware Design and Built

Figure 4.1: Final wooden Hardware Board with Frets, Strings, Coils and TechnicBox

A 22 mm deep pine board with a length of 950 mm serves as the basic unit of the instrument. The hybrid instrument has a analogue sound generation that consists of four strings. The strings can be struck by hand or made to vibrate without contact via magnetic fields. The scale length of the strings - and thus the freely vibrating part - is 648 mm and thus corresponds to the scale length of a Stratocaster guitar. The strings vibrate 29 mm above the board and are tuned in E, G, B, E. The tuning for sure can always be changed. The distance between the strings is about 15 mm at the nut and about 20 mm at the bridge.

Figure 4.2: Disassembled Piezo PickUp as part of the Bridge

The string spacing and the string height are determined in particular by the copper wire coils located under the strings near the bridge. Right under the Bridge sits a Piezo pickUp of type Shadow SH099 to record the sound of the string vibration, as it can be seen in Figure 4.2.

The fret rods as they can bee seen in Figure 4.1 applied to the board surface along the playing plane have no direct contact with the strings and thus have no direct sound-shaping influence. They only serve as a visual orientation for the player, to show the change in pitch over the length of the strings.

The fret spacing depends on the scale length and was calculated using [50]. Most of the hardware was made in a wood workshop in Berlin, Germany. See Appendix X for photographic documentation of the wood and hardware fabrication. Picture one shows different views of the finished instrument and its functions.

Technically, the instrument can be divided into two independent parts. On the one hand, there are the electrical circuits that can excite the strings to vibrate by generating magnetic fields. On the other hand, the recording of the string vibration via a piezo pick-up and signal processing with the Bela microcontroller. These two parts are discussed separately below.

4.1 Electrical circuits for the excitation of string vibration

Figure 4.3: Detail view of the coils and potentiometers of the EBow Circuit

For the analogue circuit, a total of 8 coils were installed directly below and as close as possible to the strings. This means that the implemented electrical circuit provides two coils per string. These are the transmitter and receiver coils of the circuit. Details of the implemented circuit are documented in section 2.3.2.

To accommodate the coils, wooden pieces of (LxWxH) approx. 100 x 30 mm x 20 mm were drilled and the coils inserted. The transmitter coil sits close by the bridge, as can be seen in Fig. 4.3.

Here the deflection of the strings is the smallest, which is why the coil head can come as close as possible to the string without running the risk of touching it when it vibrates. In the course of the tests carried out, it also became apparent that the induction of the vibration by the magnetic field directly at the coil can lead to a high proportion of overtones. The resulting signal sounds brighter and fuller.

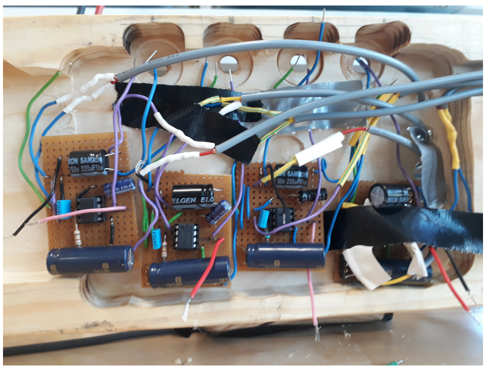

Figure 4.4: Soldering the EBow circuits on the back of the board

The wiring for the coils runs underneath the coil sockets through holes to the back of the board. The electronic circuits (EBow Circuits in this case) are stored on the back. Each of the 4 EBow Circuits has a size of (LxWxH) approx. 45 mm x 30 mm x 15 mm. To accommodate the technology, areas approx. 15 mm deep were milled out of the wood on the back of the Instrument board.

The operational amplifiers LM386, which function as the central unit in the circuit, are powered by a KSE Falken 1. The Falken power bank is actually designed for guitar pedals and offers several connections for a 9 V power supply. The wiring between the battery and the Ebow boards is not permanent. This means that the battery can be removed at any time for charging and use for other purposes.

According to the circuit in Fig. 2.2 in section 2.3.2, the current flow through the input coil can be changed with a potentiometer. The potentiometers are located in the technical grooves of the EBow Circuits and can be controlled from the top of the board (see Fig. 4.3).

4.2 Sound input, output and sensor-based control

Four faders, three potentiometers an infrared sensor and a switch button are available for control and interaction with the digital sound processing. The sensors and the microprocessor are housed in a technology box, that can be seen in detail view Figure 4.5 and 4.6 . The Bela microcontroller [25] is used as the central processor unit. It is located in the technical box directly behind the bridge. The output of the piezo pickup is connected to Bela's audio input.

Figure 4.5: Detail view of the technology box with Infrared sensor, switch control and two potentiometers

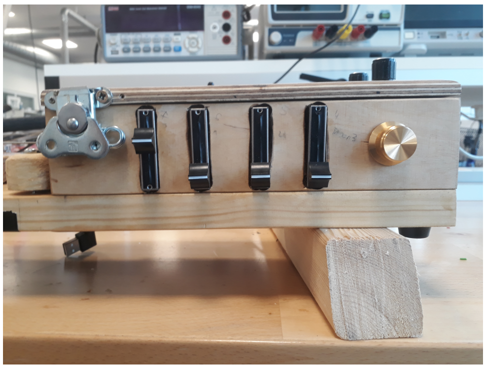

Figure 4.6: Detail view of the technology box with 4 faders and a potentiometer

As audio output - downstream of the digital signal processing - a mono jack 6.3 mm socket was installed behind the technical box and connected to Bela's audio output. The audio output is levelled at line level. The infrared sensor of the Sharp type GP2Y0A21YK0F. Has a measuring range between 10 and 80 cm. The illustration in Fig. 4.7 shows a schematic of the signal connection of the sensors and the Bela mini microcontroller. The code-implementation of the potentiometers and sensors are explained in more detail in section 5.2.

A 5V USB micro connection is provided for the power supply of the Bela microcontroller. To accommodate the battery, a corresponding area is milled out on the underside of the instrument board, similar to technical accommodation of the Falken 9V Powerbank and the Ebow Circuits. The Bela microcontroller can be started by connecting the 5 V power bank to the USB cable on the underside of the board. The technical box itself has 2 butterfly buckles. These ensure easy access to the Bela microcontroller and the sensor technology, but also allow, for example, a quick change of guitar strings.

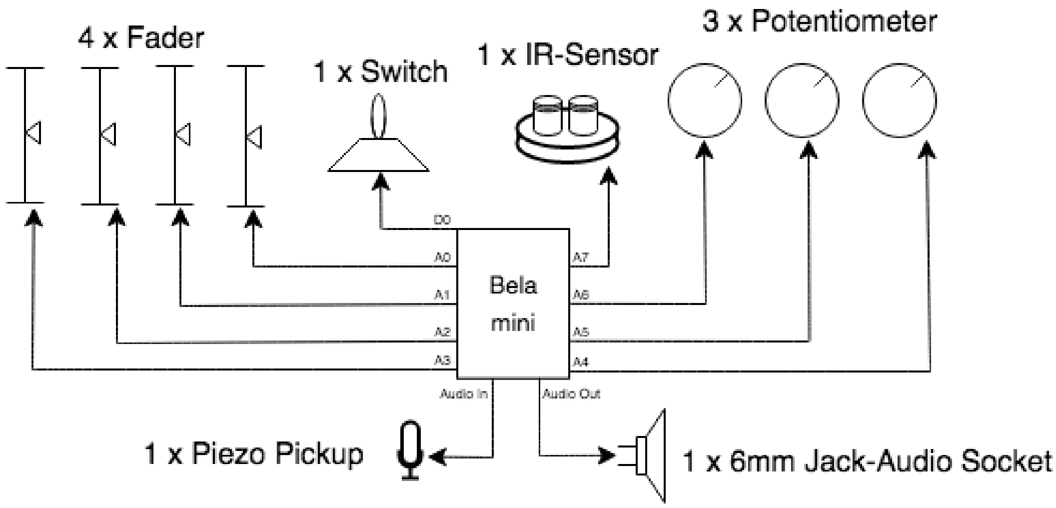

Figure 4.7: Principle image of the hardware sensore connection with the center unit of the Bela mini microcontroller

Chapter 5

Software-Implementation

The software implementation was carried out entirely with the Bela IDE [25] and is written in the C++ programming language. In addition to the input signal, two central sound generation processes are carried out in the digital sound processing. These are, on the one hand, sound-replacement by means of a wavetable buffer and the octave-modulated input signal from the harmoniser calculation in the frequency domain after inverse FFT. Figure 5.1 shows the basic routing principle in a very simplyfied way.

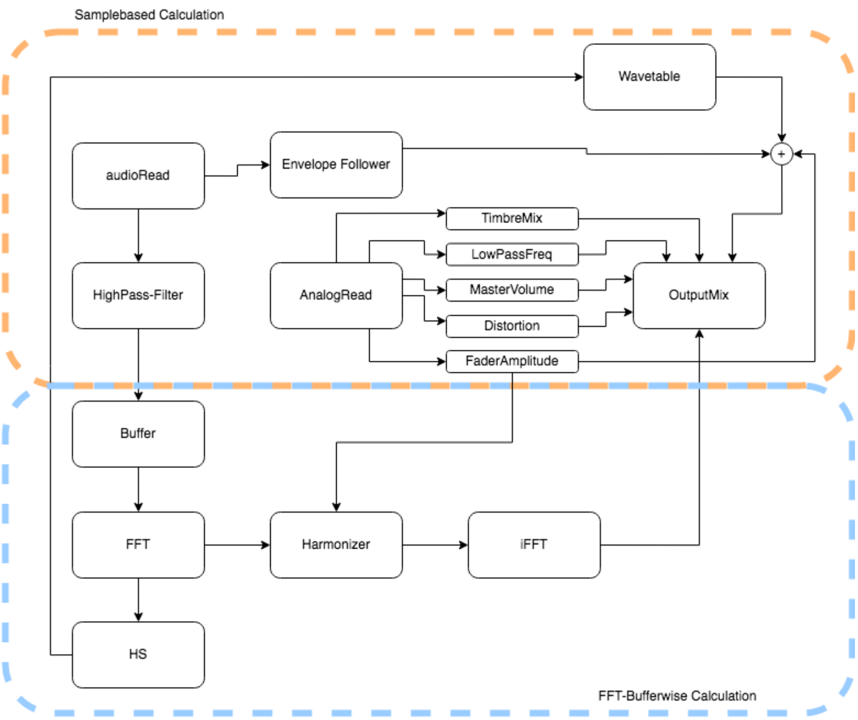

Figure 5.1: Principle image of the code's Logic connections for audio and signal routing

The calculation parts of the software implementation can be roughly divided into two blocks: One part of the software calculation steps is completely automated internally on the microcontroller and without control or interaction with the instrument player. Other parts, such as analog reads of the software implementation are designed as interfaces and can be actively controlled by the user of the instrument.

5.1 Constant internal ongoing software-processes

The input audio signal from the piezo pick-up is sampled at a sample rate of 44100 Hz. As a first step, the input signal is fed to an envelope follower calculation. The result is the positive progression of the amplitude of the input signal. In parallel, after high-pass filtering, the signal is transferred to a 1024-sample buffer, which - when filled - is fed to the FFT after multiplication by a function window. High-pass filtering is used to cut out low-frequency noise components that often have high amplitudes in audio signals and can thus influence the result of a pitch estimation, but play no particular role for the human ear. To subsequently improve the accuracy of the time-frequency resolution of the FFT result, a comparison of the phase of the signal with the frequencies of the bin edges according to [8] is carried out.

```
float phaseDiff = phase - lastInputPhases[n];
float binCentreFrequency = 2.0 * M_PI * (float)n / (float)gFftSize;
phaseDiff = wrapPhase(phaseDiff - binCentreFrequency * gHopSize);
float binDeviation = phaseDiff * (float)gFftSize / (float)gHopSize /
(2.0 * M_PI);
analysisFrequencies[n] = (float)n + binDeviation;
```

This allows a very precise estimation of the frequency to be achieved. The GUI used for testing the frequency detection algorithm is documented in Appendix B. To determine the fundamental note of a played string with its specific number of harmonics and the unavoidable noise of the piezo pickup, the FFT data buffer is subjected to harmonic summation (cf. section 3.2). In the present case, the frequency is searched in a range between 100 Hz and 1000 Hz with 3 harmonics and a resolution of 0.1 Hz of the underlying search grid.

The FFT and the pitch detection algorithm are executed in the Bela-IDE as an auxiliary threat. This means that they do not have the same priority as other calculation steps in the sample-wise render function. By moving the calculation to an auxillary threat, the software environment is not bound to complete the FFT and pitch estimation within the specified time period of a sample-wise calculation step. The calculation can be distributed over several calculation steps using free capacities. The probability of audio dropouts is reduced.

```
AuxiliaryTask gFftTask;
void process_fft_background(void *);
gFftTask = Bela_createAuxiliaryTask(process_fft_background, 50,
"bela-process-fft");
Bela_scheduleAuxiliaryTask(gFftTask);
```

Once the result of the pitch detection algorithm is available, the speed with which the readpointer reads the samples of the wavetable (corresponds to the frequency) is adjusted. Despite numerous optimisations in the pitch detection, false detections or jumps still occur. The change in readpointer speed is therefore subjected to smoothing, in the sense of low-pass filtering. The smoothing and the low-pass filtering in the range of a few milliseconds leads to an audible and perceptible latency in the audio adjustment. The synthesised audio signal follows the audio input signal with a slight delay. This solution represents a compromise between the desire for real-time processing and the necessary precision of pitch detection. Other algorithms for pitch detection, e.g. in the time domain with the YIN alogorithm [9], were tested in another project [41]. Due to the robustness of harmonic summation with regard to noises with a large dynamic range and disturbance signal components such as noise, harmonic summation was given preference.

The result of the aforementioned calculation steps can thus be considered a sound-replacement acting in real-time. The fundamental note of the incoming audio signal is determined and a digitally generated sound is pitch-adjusted accordingly. The generated signal is then multiplied by the result of the envelope follower, which is why the generated signal not only follows the pitch curve, but also the volume curve of the input signal.

Furthermore, the result of the FFT is harmonised in the frequency domain and fed to an inverse FFT. The result is a octave-shifted variants of the input signal.

```
int newBin = floorf(n * gPitchShift + 0.5);
synthesisFrequencies[newBin] = analysisFrequencies[n] * gPitchShift;
```

5.2 Interface and sensor-based control of the software

A Timbre Mix fader (see Figure 4.6 - the golden metallic fader on the right side) is provided to crossfade between the two central sound generation processors, whereby the full left position reproduces the pure wavetable signal and the full right position the pure harmoniser signal.

The 4 SlideFaders control the amplitude of each of the four octaved signal components of the two basic sounds in comparison to the input signal. If the 4 slide faders are all in zero position, the input signal is output unchanged. If one or more fader positions are increased, the proportion of the syntetic signal in the output signal is increased. If all 4 slide faders are in the upper position, only the synthetic signal of the wavetable or the harmoniser is output.

Two more rotary potentiometers, a switch knob and an infrared sensor are mounted on the top plate of the technology box, see Figure 4.5. One Potentiometer controls a biquad lowpass filter with a preset Q-factor of 10. The Bela-IDE-biquad-library was used for the implementation.

The second rotary potentiometer controls an overdrive algorithm. This simply controls the drive of the atan function (see section 3.6). The infrared sensor is mapped to the master output volume. The switch position of the verifies whether the control of the master output volume is active or not.

Chapter 6

Description of the playing process

As with many other NIME projects, the form of interaction is not rigidly prescribed, but rather open to the players' willingness to experiment. It is desirable that players find their own approach to the instrument. The instrument board can be placed horizontally on the table in front of the player or placed on the lap. Other playing positions are possible. Conceivable the instrument can also be held horizontally, similar to a sitar, in which case the saddle is at or above head height and the sensor system in the technical box can be placed in the groin area on the player's lap. It is also possible to carry the instrument with a strap around the chest similar to an electric guitar, although no corresponding suspensions have yet been fitted for this. In its current state, the instrument is designed for right-handed players. By reversing the order of the strings, however, the playability can also be made accessible to left-handers. Depending on how the instrument is placed, parts of the potentiometers may be located on the opposite side of the instrument from the player and become harder to reach. The strings can be excited by the plug of a hand, or by the contactless vibration excitation of the magnetic fields or both at a time. For strumming, i.e. the fast striking of several sides with a finger or a pleck, the string spacing is somewhat large. In the tests carried out so far, single string finger picking was preferred. For pitch control, the fretless instrument can be played similar to a slide guitar with a bottleneck or other objects with one or both hands. Since strings sometimes sound permanently due to the non-contact excitation, it is at the player's discretion to also mute them while playing. If the pitch is played with one hand like on a traditional guitar or slide guitar, the other hand is available to play the Master-Volume touch-free via the infrared sensor and to adjust and change the timbre changes while playing.

Video of playing examples of the instrument can be found here:
`https://youtu.be/ydESeg1h6xs`
`https://youtu.be/E9poKkKcjx0`

Chapter 7

Project Assessment

7.1 Evaluation

Generally in the NIME-community, a basis of knowledge and discussion on how design parameters can be summarised and how DMIs can be evaluated has been carried out, e.g. [6], [30], [5]

For the evaluation within the framework of this project, a separate approach deviating from the standard methods was chosen, since in particular open questions arose from the design process and the limited time available did not allow for a comprehensive investigation and approach according to the recommended methodology. The instrument was set up and put into operation in a room at Aalborg University on 22 May 2023. For the testing it was connected to a HK Audio Premium PR:O Move 8 loudspeaker without any further effects or sound modulation.

Fig. 7.1 shows the set up of the Evaluation for the subjects

A total of 7 people took part in the evaluation. Each test person received a short introduction to the different functions of the instrument. Equipped with this knowledge, the test person was asked to perform various tasks. These tasks included trying out different postures of the instrument freely, as well as technical aspects such as operating different effects and sensors, such as the filter knob, the infrared sensor and playing a simple sequence of notes on the instrument. The tasks were performed in the presence of and in con-

Figure 7.1: Set up for the evaluation testing in a seminar room at Aalborg University

sultation with the experimenter and are not to be understood as test tasks in the sense of a pass or fail. The tasks were primarily intended to lead to a better understanding and familiarity with the instrument.

After performing the tasks, each test person was given a freely chosen time to play the instrument and to explore it playfully. When the test person indicated that they had spent enough time playing, they were asked to fill in a questionnaire. For the free playing and the subsequent filling in of the questionnaire, no assistance was given by the experimenter.

Since the number of test persons was small, a qualitative questioning was aimed at in particular. Thus, more open questions were asked, which could be answered openly by the test persons. Personal data was not collected. There was also a conscious decision not to ask about background data, like a music sophistication index of the subjects that could allow more in-depth classification for the data assessment. The group of test persons was considered homogeneous in that it consists exceptionally of students of Sound and Music Computing course at Aalborg University. All participants have been educated in DMI design and gained experience by designing their on NIME. Therfor all feedback is considered equal accordingly.

The full questionnaire is documented in Appendix C.

The results worth highlighting are discussed in the following. The length of time it takes a beginner to "master" the instrument, whereby "mastering" was not further specified in the question itself, was given by the test persons as at least 6 months up to 15 years. The mean value of all statements is about 6 years, which is needed to learn the instrument and to be able to play it well. Most of the test persons agreed that the instrument is more advanced to learn, compared to an ordinary slide or lap steel guitar. 5 of the 7 test persons stated that it would be more difficult to learn the instrument than an ordinary slide or lap steel guitar. One person stated that it would be equally difficult and one person felt that it might be easier to learn the instrument than an ordinary slide or lap steel guitar. There was a high level of agreement that the frets help to play melodies. The question resulted in a mean score of 4.4 on the 5 point scale, with 5 being "Yes, they are very important" and 1 being "No, I don't see any use". Positive feedback for the design came from the question of how well the sound and feel of the instrument fit together. On the 5-point scale, where 5 points were given as "sound and feel match perfectly" and 1 point as "sound and feel diverge very much", the match between feel and sound was given an average of 4.0 points. The number of sound adjustment possibilities provided with the instrument was also rated positively by the test persons with a mean of 3.85 points. Here the answer options ranged from 1 with "The sound adjustment possibilities are not sufficient at all" and 5 with "The sound adjustment possibilities are perfect. I wouldn't change anything".

When asked how much the test persons would expect an instrument to cost in a musical instrument shop, the evaluation of 6 of the 7 test persons showed a range between 1500 and 5000 Danish Kroner (approx. 200 - 670 €), with a mean value of approx. 2900 kr, i.e. approx. 390 €. The 7th test person stated that he/she would expect a price of 40,000 kr., i.e. approx. 5,400 €. This question deliberately implies a kind of "willingness-to-pay" assessment, which in survey practice can say a lot about the value of an object or attribute. Of course, in the context of the evaluation conducted, the statement should be viewed with caution due to the small number of participants and the unidentified background of the test persons. Lapsteel guitars available in specialised shops start at just below 7.000 kr or 100 € [15]. Higher-priced models reach prices of up to about 20,000 kr or 3,000 € in common online shops. The assessment of the test persons shows me in particular that the test persons did not have the feeling of playing a professionally manufactured and high end instrument. This is not surprising because of the self-made character of the board compared to industrially manufactured instruments. With an average value of 2900 kr or, taking into account the "outlier" in the averaging of 8200 kr (390 or 1.100 EUR), the instrument is neither to be found in the cheapest or below the cheapest price sector of available instruments. This shows a potentially higher value compared to cheapest instruments, which could come from the implemented technology, making the instrument unique and augmented. In this project, no cost calculation of the materials used nor of the time needed for the production was made. The manufacturing costs for the construction of individual pieces and prototypes cannot be compared with industrially mass-produced products.

Essential for the evaluation of the functionality of the pitch detection algorithm was the question "How precise is the pitch detection algorithm working? Could you hear wrong tuning and/or distraction sounds?" All subjects had received an introduction to the instrument, with an explanation of how the pitch estimation works and how it is implemented. The result to the question was satisfactory with a mean of 3.3 on a 5-point scale. 1 Point out of 5 was explained as "The pitch detection works really badly and adds way to many disharmonies for good playing experience" and 5 points out of 5 as "I didn't notice any wrong tuning by the wavetable-sound-replacing through the pitch detection algorithm". As the slide guitar is a fretless instument, playing it in pitch is very difficult to master. It wasn't investigated further, if the subjects could distinguish between disharmonics introduced by general playing modalities, like holding the bottleneck accurate or other pitch affecting parameters, like string tuning, fret- and tonal distance, etc. or if they had been able to certainly qualify the pitch detection algorithm in their assessment.

The need for improvement of the instrument mentioned by the subjects in the open questions has two main core issues. On the one hand, some of the test persons felt that the infrared distance sensor requires adjustments and is not yet fully integrated as a complete tool in the playing process. Secondly, the test persons complained that the potentiometer of the analogue EBow circuits only has a small sweetspot and that the different circuits sometimes led to different degrees of vibration of the strings, which meant that the control of the magnetic vibration did not allow the desired degree of precision. One person mentioned that the look of the instrument could be improved.

It is worth noting that one test person identified the bottleneck itself as potential for optimisation. For the evaluation, only a round metal bottleneck was provided for playing the pitch along the strings, although other objects could of course also be conceivable (cf. section 6).

Taken from the feedback, a few quotes describing the feeling of playing:

- „you can get a lot of cool sounds that you didn't expect getting“
- „Sometimes the sound can suddenly be very harsh“
- „I thought it was interesting to have the strings vibrate on their own"
- „I think that this NIME can provide a very different experience from a slide guitar“
- „I really liked the effect of the mixer knob (timbre mix) since allows you to blend "digital" and "analog" sounds in a very expressive way“
- „It stands on its own, affording creative capabilities to the user and having a great balance of number of included features.
- „The feel of the ebow-driven strings, coupled with the slide; a great tactile feedback sensation.“

7.2 Potential for improvement/further research

During the design and editing process, numerous learning experiences were gained, decisions were made and compromises between idea and technical feasibility were worked out. As the author of this document and executor of this Master's thesis project, I probably have the most critical view of the processes myself. Even if the testers of the evaluation basically attest sufficient features to the instrument, it should be the intrinsic striving of a student, developer and researcher to improve and critically evaluate the own process. The following list is to be understood as a collection of experiences and thoughts, sometimes details, and is not necessarily complete or conclusive in sum, nor is it intended to diminish the overall outcome of the work.

The project clearly showed me the limits of real-time processing in relation to the available computer power. Design and prototype approaches, in which instead of a signal sum from the piezo pickup, several pickups (e.g. SingleCoils , cf. Annex

A) were planned and worked with in combination with a Bela microcontroller audio channel extension, the Bela Audio Expander [25], had to be discarded, because a multi-audio read of several channels with the corresponding pitch stimulation could not be operated simultaneously with the sensor data readout at 8 analogue inputs. The Bela microcontroller had simply reached the limits of its capacity. The use of a single-coil audio capture of all 4 strings would have been particularly advantageous for the subsequent FFT. The currently implemented algorithm considers the signal as if it were a monophonic signal and finds the salient fundamental frequency of a tone of the sound mixture. Since the pitch estimation lies in the harmonic profile of the input signal, the sound replacement does not particular sound wrong or disharmonic. It is just not as precise as it could be if each signal could be captured and analysed separately. A more detailed knowledge of the input signal would also have allowed the implementation of further DSP effects, such as the digital creation of arpeggios, the addition or deletion of various harmonic components. Instead of the individual detection of each string, there are also DSP solutions, namely algorithms that allow multi-pitch estimation [10]. However, these are computationally even more complex than the already latency-laden FFT and HS. Fast models are mainly found in the field of AI or source separation and require prior training. Source separation algorithms in particular are easier to use for pitch recognition on pitch-dictated musical instruments. For fretles instruments and thus continuous pitch timing, pretrained algorithms are more difficult to implement. The possibility of inserting a physical model instead of a wavetable approach for the digital sound synthesis, which would allow a higher degree of parameterisation for the sensor-controlled interaction, had to be discarded in the prototype status because the computing power of the Bela microcontroller with constant FFT and pitch estimation was largely exhausted.

However, computer power could possibly also be saved by optimising the code further. Perhaps leaner physical models, such as waveguide modelling instead of the finite-different schemes should have been tried out in protoytpe state and would have been a better option. The platform and code resources are like a playground. If the scope of the Master's thesis had allowed it, further efforts would definitely have gone into code optimisation and sound design and extending the interactive possibilities for sensor-controlled sound controllers. This also raises the question of how much possibilities for interaction in a DMI makes sense at all. The testers of the evaluation found the number of sensor-controlled sound adjustments to be at least sufficient and satisfactory.

In the context of the present work, I dared to leave the area of the digital sound control at times and to work with analogue technology. This was mainly due to the fact that in prototype status the analogue circuit of the Ebow was superior to the DSP-controlled circuits, as it allows a direct feedback connection between the received signal and the magnetic transmitting field and does not require the diversions via the A/D and D/A conversion of a signal that is necessary for the DSP. This "excursion" into the analog circuit on the one hand been an enormous extension of my learning experience of this project, but has also been marked by numerous time-consuming obstacles. At this point I would like to thank Jesper Greve, whose calm and relaxed manner and knowledge of analogue electronic circuits persuaded me to persevere and continue. Although I tried to fully understand, calculate and model the processes in the implemented circuit in the sense of a scientific approach, I honestly did not fully succeed in understanding all the influencing parameters of the EBow circuit within the time available. The interaction of the components with each other with feedback and loop connections would have gone beyond the scope of the project and left the focus of my studies. Nevertheless, I think I have succeeded in building up a good understanding of the circuits and in extending the principle of EBow for my area of application. The findings from the evaluation could have been improved if stakeholders, such as musical instrument shops, manufacturers of music controllers or professional slide guitar players, had been consulted. This was not possible within the framework of the master's thesis.

Chapter 8

Summary

Figure 8.1: A foto of the final instrument [25]

Traditionally, musical instrument making is a very slowly evolving craft. The families of instruments known to us have existed in their present form for many centuries. Within the framework of this work, the goal in the design process was not to completely break with these traditions, but to design a new instrument that ties in with the existing forms of well-known instruments. As a long-time guitarist, stringed instruments have a special appeal for me.

If you think about how long it takes to learn an instrument, it becomes clear that the frets of a guitar support an intoned playing style and therefore help to be able to play harmoniously with other instruments faster. A s lap steel or slide guitar is superior to a normal guitar in that the tones are played without frets. This poses a higher learning challenge, but also allows for nuance and musical expression not possible with a fretted instrument.

In the context of previous experiments and projects as well as my previous professional activity as an engineer in the field of technical acoustics, I am also particularly interested in the sound properties of resonance processes. This framework gave me the idea of an instrument that develops and expresses a form of its own life through feedback and resonance processes, as well as code-based control through digital sound processing, taking into account signal analysis and robotized excitation. The player should be brought from the position of activator to a position of reacting. The instrument should be able to produce tones or melodies itself. The musician should be able to interact with these sounds at any time.

As part of the work, numerous different ways of realizing this robotized variety were tested. After an extensive prototype phase, the final design was determined and only the selected part of the technology was considered in the final instrument. Accordingly, this paper has been divided into two parts, the main document that contains only the techniques used in the final instrument and the appendix, that hold further information about tested techniques along the way. A literature review of other instrument designs and commercial available products was also performed. The present work can therefore be regarded as an up-to-date reference work, which documents the current development in the area of DMI construction and the construction of new stringed instruments, as well as lists products and technical solutions in the area of vibrating strings and sustain, even if they couldn't all had been tested. The intention was to create an explanatory work that can help interested people, such as other DMI builders to better understand various techniques examined within the scope of this project and, if wished, to implement them themselves. It has been successfully achieved to make the strings of the instrument vibrate without touch and to such an extent that the natural vibration is loud and clearly perceptible and even when playing the string with a bottleneck it produces a continuous, endlessly sustain-sounding constant tone.

The sound processing is computed in real time and should not have any latencies that affect the playing feel. For this purpose, a powerful micrcontroller Bela was used in C++. But even on a microcontroller like Bela, the real-time processing of audio signals has its limits. In order for digitally produced sounds and effects that support the original analog signal of the guitar to adapt harmoniously to the playing movement and interaction of a musician, methods for amplitude and pitch detection and tracking are implemented. Simultaneous fretless playing from several sides and their signal analysis is truly a big challenge for a microprocessor in real time. Accurate methods for multiple pitch estimation are computationally expensive and often do not work in real time. Trained models are better suited to instruments with discrete fret tones. A large part of this work has therefore been spend on an implementation of harmonic tracking and its verification. Ultimately, a variant of harmonic summation in the frequency domain was chosen.

The pitch estimation made it possible not only to give the instrument sound effects and modifications, but also to completely change the sound. A corresponding sound replacement sound engine based on wavetable synthesis was integrated.

Since self-excitation frees up capacities in the player - normally two hands are always needed to play a stringed instrument, one hand for changing the pitch, another hand for the excitation - various sensors are provided that enable the interaction and extend the instrument compared to ordinary slide guitars.

The playful and tonal experience was consistently rated as good by the testers during the evaluation. It became clear that the test subjects could understand the instrument and its functions, but that they were not able to play intoned right away. The length of time it takes to learn the instrument was estimated as an average of around 6 years. In addition to the tonal possibilities, the test subjects were particularly impressed by the feel and the feeling of playing an instrument with self-vibrating strings.

Bibliography

[1] Alex12349. *Make a E-bow Variant*. 2010. URL: https://www.instructables.com/make-a-E-bow-variant/.

[2] Daniel Arfib, Jean-Michel Couturier, and Loic Kessous. "Expressiveness and Digital Musical Instrument Design". In: *Journal of New Music Research* 34 (Mar. 2005), pp. 125–136.

[3] Jack Armitage, Fabio Morreale, and Andrew McPherson. "The finer the musician, the smaller the details: NIMEcraft under the microscope". In: (June 2017), pp. 393–398.

[4] Jack Armitage et al. "The proto-langspil: launching an Icelandic NIME research lab with the help of a marginalised instrument". In: *New Interfaces for Musical Expression proceedings* (2022).

[5] Aaron Bangor, Phil Kortum, and James Miller. "Determining What Individual SUS Scores Mean: Adding an Adjective Rating Scale". In: *J. Usability Stud.* 4 (Apr. 2009), pp. 114–123.

[6] Jeronimo Barbosa et al. "What does " Evaluation " mean for the NIME community?" In: May 2015.

[7] Scott Barton, Ethan Prihar, and Paulo Carvalho. "Cyther: A human-playable, self-tuning robotic zither". In: May 2017.

[8] @BelaPlatform. *C++ Real-Time Audio Programming with Bela*. Apr. 2021. URL: https://www.youtube.com/@BelaPlatform.

[9] Alain de Cheveigne. In: *Ircam-CNRS, 1 place Igor Stravinsky, 75004 Paris, France Hideki Kawahara, Wakayama University* (2002).

[10] Mads Græsbøll Christensen et al. "Multi-pitch estimation". In: *Signal Processing* 88.4 (2008), pp. 972–983. URL: https://www.sciencedirect.com/science/article/pii/S0165168407003581.

[11] Perry R. Cook. "Principles For Designing Computer Music Controllers". In: (2001). URL: https://zenodo.org/record/1176358.

[12] Hard Driver. *Sustainer Installation Kit*. May 2023. URL: http://hdsustainer.com/.

[13] TC Electronics. *The Aeon*. May 2023. URL: `https://www.tcelectronic.com/tcelectronic/product?modelCode=P0DAS`.

[14] Fishman. *Triplay - The Ultimate MIDI Guitar Controller*. May 2023. URL: `https://www.fishman.com/tripleplay/`.

[15] Thomann GmbH. *Harley Benton Slider II Lapsteel*. May 2023. URL: `https://www.thomann.de/de/harley_benton_slider_ii.htm`.

[16] Robert Jack. "Tangibility and Richness in Digital Musical Instrument Design". In: (Mar. 2019). Thesis for PhD, Queen Mary, University of London, March 2019.

[17] Sergi Jordà. "Digital Instruments and Players: Part I – Efficiency and Apprenticeship". In: *Proceedings of the International Conference on New Interfaces for Musical Expression* (Hamamatsu, Japan). Zenodo, June 2004, pp. 59–63.

[18] Joyo. *JGE-01*. May 2023. URL: `https://ebow.com/faq.php`.

[19] JustinBeckner. *The Quest for Infinite Sustain: The EBow Explained*. Nov. 2018. URL: `https://www.ultimate-guitar.com/articles/features/the_quest_for_infinite_sustain_the_ebow_explained-81306`.

[20] Steven Kemper. "Tremolo-Harp: A Vibration-Motor Actuated Robotic String Instrument". In: *Proceedings of the International Conference on New Interfaces for Musical Expression* (Birmingham, UK). Zenodo, June 2020, pp. 301–304.

[21] Victor Lazzarini. "Eduardo R. Miranda and Marcelo M. Wanderley: New Digital Musical Instruments: Control and Interaction Beyond the Keyboard". In: *Computer Music Journal* 31.4 (2007), pp. 75–77.

[22] Sang-won Leigh, Abhinandan Jain, and Pattie Maes. "Exploring Human-Machine Synergy and Interaction on a Robotic Instrument". In: *Proceedings of the International Conference on New Interfaces for Musical Expression* (Porto Alegre, Brazil). Zenodo, June 2019, pp. 437–442.

[23] Giacomo Lepri et al. "Play Make Believe: Exploring Design Fiction and Absurd Making for Critical NIME Design". In.

[24] Giacomo Lepri et al. "The 10, 000 Instruments Workshop - (Im)practical Research for Critical Speculation". In: *22nd International Conference on New Interfaces for Musical Expression, (NIME)*. nime.org, 2022.

[25] UK Augmented Instruments Ltd in London. *Bela embedded computing platform*. May 2023. URL: `https://bela.io/`.

[26] MarkGutierrez. *Great Guitar Build Off 2022 - Mechanical Sustainer - Gjrone Ep1 Freestyle Competition*. Apr. 2022. URL: `https://www.youtube.com/watch?v=7cn15xneIw8`.

[27] Andrew McPherson. “The Magnetic Resonator Piano: Electronic Augmentation of an Acoustic Grand Piano”. In: *Journal of New Music Research* 39.3 (2010), pp. 189–202.

[28] Andrew McPherson and Giacomo Lepri. “Beholden to our tools: negotiating with technology while sketching digital instruments”. In: *Proceedings of the International Conference on New Interfaces for Musical Expression* (Birmingham, UK). Zenodo, June 2020, pp. 434–439.

[29] Takumi Ogata and Gil Weinberg. “Robotically Augmented Electric Guitar for Shared Control”. In: *Proceedings of the International Conference on New Interfaces for Musical Expression* (Copenhagen, Denmark). Zenodo, June 2017, pp. 487–488.

[30] Sile O’Modhrain. “A Framework for the Evaluation of Digital Musical Instruments”. In: *Computer Music Journal* 35.1 (Mar. 2011), pp. 28–42.

[31] Gary T. Osborne and Alan A. Hoover. *Sustainer for a musical instrument*. Patent Number: 5,932,827. Aug. 1999. URL: `https://patentimages.storage.googleapis.com/26/7f/30/2241ddc8926e32/US5932827.pdf`.

[32] Heet Sound Products. *The Amazing EBow*. May 2023. URL: `https://ebow.com/`.

[33] Rob o Reilly. *Expressiv MIDI Pro 2 - MIDI Guitar*. May 2023. URL: `https://www.rorguitars.com/products/expressiv-midi-pro`.

[34] J.D. Reiss and A. McPherson. *Audio Effects: Theory, Implementation and Application*. Taylor & Francis, 2014. ISBN: 9781466560284. URL: `https://books.google.dk/books?id=z5DaBAAAQBAJ`.

[35] Cycfi Research. *The Nu modular single-string pickups*. May 2023. URL: `https://www.cycfi.com/projects/nu-v2-capsule/`.

[36] Stephen Roddy and Brian Bridges. “Mapping for meaning: the embodied sonification listening model and its implications for the mapping problem in sonic information design”. In: *Journal on Multimodal User Interfaces* (June 2020).

[37] Paul Rubenstein. *Ubertar Hexaphonic Pickups*. May 2023. URL: `https://ubertar.com/hexaphonic/one_and_two_string_pickups.html`.

[38] Eric Singer and Pat Metheny. *Orchestrion and LEMUR: League of Electronic Musical Urban Robots, a group of artists and technologists who create robotic musical instruments*. 2000.

[39] Jeff Snider. *Electrosteel*. May 2023. URL: `https://www.scattershot.org/electrosteel.html`.

[40] SOMA. *DVINA*. May 2023. URL: `https://somasynths.com/dvina/`.

[41] Sound and Music Signal Analysis. *Study Subject of the Sound and Music Computing Program*. May 2023.

[42] Sound and Music Computing. *Program Master of Science (MSc) in Engineering*. May 2023. URL: https://www.smc.aau.dk/.

[43] Sustainiac. *Stomp Model*. May 2023. URL: https://www.sustainiac.com/.

[44] @VegasCyclingFreak. *DIY Ebow Using Internet Schematic - Does It Actually Work?!, Ebow Resurrection Part III - FINALLY CRACKED!!!, Ebow Resurrection Attempt Part II - SUCCESS?!, Ebow Resurrection Attempt Part I - A Hard Task!, All Of Those Ebow Schematics You've Seen ARE WRONG! (Part II), All Of Those Ebow Schematics You've Seen ARE WRONG! (Part I)*. 2023. URL: https://www.youtube.com/@VegasCyclingFreak/videos.

[45] Travis J West, Marcelo Wanderley, and Baptiste Caramiaux. "Making Mappings: Examining the Design Process". In: *Proceedings of the International Conference on New Interfaces for Musical Expression* (Birmingham, UK). Zenodo, June 2020, pp. 291–296.

[46] Wikipedia. *Piano*. May 2023. URL: https://en.wikipedia.org/wiki/Piano.

[47] Wikipedia. *String instrument*. URL: https://en.wikipedia.org/wiki/String_instrument.

[48] Wikipedia. *String vibration*. URL: https://de.wikipedia.org/wiki/Saitenschwingung.

[49] Wikipedia. *Trumpet*. May 2023. URL: https://en.wikipedia.org/wiki/Trumpet.

[50] Strings Wood Custom Guitars Frank Zillmann. *Bundabstand berechnen*. May 2023. URL: https://stringsandwood.de/index.php/informationen-zum-gitarrenbau/bundabstand-berechnen/.

Appendix A

Prototype-tested designs and variants

A.1 Alternative methods for recording string vibrations

A.1.1 Single Coil Pickups

In electric guitar construction, magnetic pickups are often used to record the string vibration. Electric guitar strings, unlike strings on an acoustic guitar, are made of a magnetisable metal. This is usually nickel, cobalt, chrome or steel. An electric guitar pickup consists of a cylindrical magnetic core wrapped by a conductive wire in the form of a coil. If the vibration of the string changes the magnetic field of the magnetic coil, a voltage change is triggered in the coil and a current is induced. The induced voltage depends on numerous properties, such as the magnetic field strength, the number of coil windings and the distance between the magnet and the string.

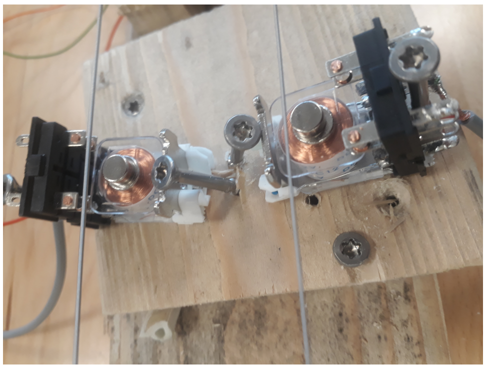

Figure A.1: Dismantled 12V DC Relay Coils for single string pickup

Commercial products of single coils are available, e.g. [37], [35]. The idea to use the coils of 12V DC Relays for single pickup i first found on [26].

Single Pickups allow - compared to multi string single coil or humbucker pick ups as they are commonly used in electric guitars - the post processing of each strings individually. A device with option for multi-channel A/D convertion is needed.

A.1.2 Multi Channel AudioExpander

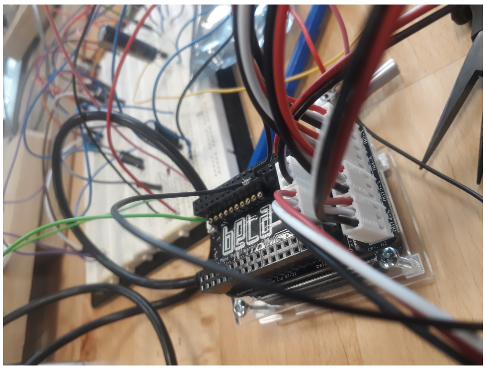

Figure A.2: Bela AudioExpander [25] as used in the prototype State

In this project I experimented with single-coil audio capture in combination with the Bela Multi Channel Expander. The Bela Multichannel Expander allows additional audio capture and A/D conversion of up to a total of 8 audio in and 8 audio out. However, during the prototype status, a stress test revealed that the use of all 8 analogue read channels plus 4 audio in plus the on-board implemented DSP, such as FFT and pitch estimation, caused overload in the Bela hardware. The CPU load of Bela was too high, so that in this project I had to switch to a piezo pickup that combines all string vibrations to a single audio stream.

A.2 Alternative method for contactless excitation of string vibration

A.2.1 Working principle Permanent magnets 12V DC rotary motor

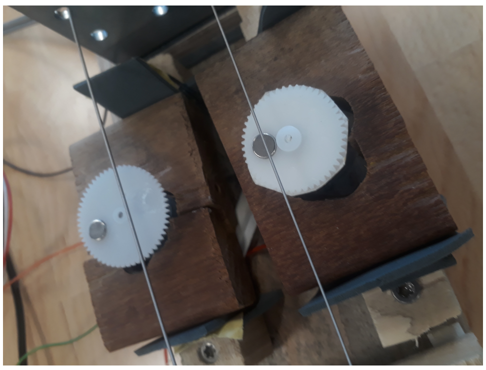

Figure A.3: Top view of two rotary motor with plastic capes and a magnet installed underneath the string of the prototype

Since electric guitar strings are made of magnetisable metal, a permanent magnet has the ability to attract and deflect them from their rest position. Even if no complete contact is made between magnets and a string, in the case of a magnet at rest, a new rest position of the string can be reached, which is in force equilibrium between the tension of the string and the magnetic force. If a magnet is moved across an electric guitar string at a close distance, the string will follow this movement. If the magnet moves too far away from the string the string will swing back to and around its original rest position. A moving permanent magnet can thus cause a string to vibrate without contact. A technically simple way to move a magnet is, for example, with rotating toy DC-motors, which are usually operated in a voltage range between 3 and 5 V, as demonstrated in [26]. Here, rotational speeds can be achieved that are sufficient to move the string. If the movement of the magnet over the string is carried out in the frequency of the string's natural vibration or in one of its divisors/multiples, the magnet can amplify the vibration of the string with each pass-by. If the movement across the string takes place at a frequency that runs counter to the string's natural vibration, the magnetic field can suppress the string's vibration. It should become clear that there is a strong correlation between rotation speed and pitch. The wrong rotation speed can suppress interaction possibilities of an instrument. Therefor it is difficult to achieve the desired precision for setting the rotation speed. A complex code-control with Pulse Width Modulation (PWM) to adjust the rotation speed in real time when playing different pitches on a string was implemented in the prototype, but not very accurate. Other insurmountable disadvantages of working with rotary motors are their inherent noise and structure-borne sound excitation during fast rotation. A possible concept using rotary motors for touch free string excitation would have entail a complete acoustic decoupling and the best possible soundproof enclosure to reduce airborne and structure-borne noise,

A.2.2 Working principle of DC-Electromagnets

A magnetic field of varying strength, which is capable of exciting a magnetisable electric guitar string to vibrate, can also be generated with electromagnets. Just as described for coils in an AC circuit in section 2.3 directional magnetic field is formed around the coil of Electromagnets in DC circuits.

If the DC-voltage applied to a coil is switched on and off - which was tried out in the prototype state using a Mosfet switch, controlled by digital Out Pin of the Bela-Controller, the magnetic field builds up and decays accordingly. The build-up and reduction of the magnetic field as a result of a voltage switch on and off is subject to a time delay due to Inductance and phase shift of Voltage to current as explained in section 2.3. If an DC-electromagnet is switched very quickly, it is therefore possible that it is no longer able to react to the rapid changes and no longer lets any current through. Voltage peaks occur in the circuit due to the delay deload of the coil and can harm other components or introduce hearable clicking in other magnetic components nearby. Otherwise, the technique works well and depending on the magnetic and current flux strength as well as the circuit times, a string can be excited to vibrate with it

A.2.3 Working principle of structure-borne sound loudspeakers

Structure-borne sound loudspeakers convert electrical signals into structure-borne sound vibrations. If these structure-borne sound vibrations are introduced into a geometrically limited flexible material, such as a free-swinging plate or an instrument body, these materials begin to emit the induced surface vibrations to the surroundings in the form of sound waves and can thereby amplify or attenuate the signal depending on the frequency. Structure-borne sound loudspeakers are therefore used mainly in so-called Distributed Mode Loudspeakers (DML) or flat-panel speakers and home cinema and bass vibration furniture. In musical instrument making and NIME, structure-borne sound loudspeakers have been creatively used in many fields.

Figure A.4: Two transducers of different power assembled to the metal string holder (bridge) on the prototype

In the context of the present work, structure-borne sound loudspeakers had been tested as an amplified feedback source by inducing the vibration signal recorded by the pickups directly back into the string. The structure-borne sound loudspeaker does not touch the string, but sits on the bridge on which the string rests. By means of the structure-borne sound loudspeakers, the traditional path of vibration propagation from the string to the instrument body is thus reversed. The vibrations are transmitted from the loudspeaker via the bridge into the string and prolong its vibration. Good results have been achieved using this technique with loudspeakers of more than 3 W power. The feedback that was introduced into the string by a structure-borne sound loudspeaker led to a satisfactory vibration strength of the string itself. However, the feedback sounded thin and sinusoidal compared to the EBow circuit. Interestingly, when playing the string with the bottleneck, there were "blind spots" along the strings where the feedback worked less well. This may be related to the coupling of the transducer to the bridge, its size and coupling to the instrument body. It seemed that not all frequencies were transmitted equally to the string over the bridge. This technique was not considered in the final design, especially because the installation on the chosen instrument bridge with a built-in piezo pickup was not technically easy, as in the prototype design, where metal brackets were used. The use of this technology would also have increased the string spacing and required other compromises in the design.

Appendix B

GUI for Pitch Estimation Testing

To test the peak detection, a GUI was designed that continuously updates the results of the frequency estimation of an analysed signal. In this way, programme parameters such as FFT length, HopSize, etc. can be empirically adjusted to obtain the best match between a known input signal and the pitch estimation algorithm for the signal. The GUI has two pairs of numbers that can be matched. One is the frequency of the sine components of the input signal, the other is the frequency estimated by the algorithm. On the left side of the GUI, three additional buttons have been added that synthesise a known signal with different sine tones in the form of a harmonic series. On the right-hand side, various pitch-shift controls have been inserted to enable the effects of the harmoniser calculations to be understood.

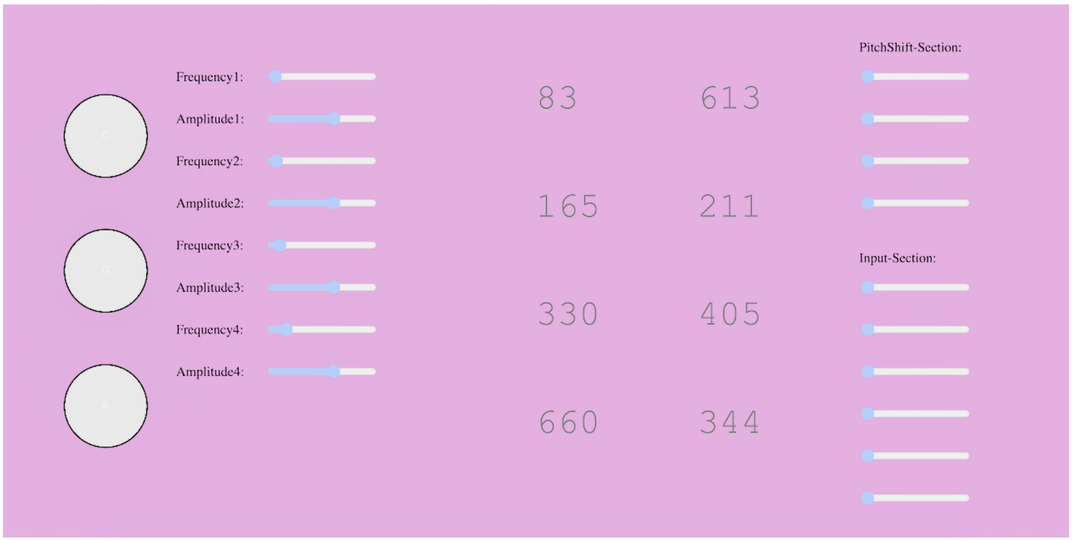

Figure B.1: Screenshot of the developed GUI in the Bela-IDE [25]

Appendix C

Questionaire Evaluation

SlideGuitar with DSP - Evaluation

Section 1

Let's start with some hands-on testing!

- Please, switch on and off all EBow-Circuits with the rotary knobs.
- Please, switch on the infrared-distance-sensor and control the output volume with your hand.
- Please, turn the Timbre-Mix-Knob all to the right and all 4 SlideFaders maximum up. This is the Harmonizer-Mode.
- Please, turn the Timbre-Mix-Knob all to the left and all 4 SlideFaders maximum up. This is the Wavetable-Sound-Replacement-Mode.

  Be aware that a pitch estimation algorithm follows your pitch playing and replaces the sound with a wavetable synthesis.
- Please vary the pitch of the strings and notice how the sound output changes.
- Please try to route the sound from the pickup through without any digital sound processing.
- Please try to play a little melody on one string. This could also be a simple scale from e.g. lower pitch to higher pitch. Please try to be precise with fulltone or halftone steps.
- Please try to play two or more strings together at one time and varying their pitch

Section 2

Now it's time for free playing and testing.

Please take your time and interact with the instrument however you want and feel.

Section3

Please answer the questions

With no previous experience of playing guitar or slide guitar, how many days/months/years do you think it takes to master the instrument?

In your opinion, is it more difficult to learn the instrument compared to an ordinary slide or lap steel guitar without DSP or EBow-Excitation?

If you don't know exactly what a slide or lap steel guitar is please look up: https://en.wikipedia.org/wiki/Lap_steel_guitar

- ☐ Same as a ordinary slide/lap steel guitar guitar
- ☐ More advanced as a ordinary slide/lap steel guitar guitar
- ☐ Less advanced as a ordinary slide/lap steel guitar guitar

Do the frets help you to play melodies?

No, i don't see any use	1	2	3	4	5	Yes, they are very important

How precise is the pitch detection algorithm working? Could you hear wrong tuning and/or distraction sounds?

The pitch detection works really badly and adds way to many disharmonies for good playing experience	1	2	3	4	5	I didn't notice any wrong tuning by the wavetable-sound-replacing through the pitch detection algorithm

Do sound and feel of playing go together?

Sound and feel diverge very much	1	2	3	4	5	Sound and feel match perfectly

Is the selection of sounds and sound adjustment possibilities sufficient and appropriate?

The sound adjustment possibilities are not sufficient at all	1	2	3	4	5	The sound adjustment possibilities are perfect. I wouldn't change anything.

How much money (in Danish Kroner) would you expect the instrument to cost in an instrument shop?

_______________ kr

Section 4

3 more open questions. Write as much as you want.

What did you notice? What works particularly well? What do you not like?

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____

____

How could the instrument be improved in your opinion?

____

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____

What name would you like best for the instrument? Please also give me your own suggestion for a name, if you dare.

- ☐ Tanker Slide
- ☐ Ghost Strings
- ☐ Biscuit Board
- ☐ Wave Slide
- ☐ The Resonance Slider Board

____