Development of a Hexaphonic Pickup for Electric Guitars and Conversion of Analog Sound into the MIDI Format

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1 Abstract

Unlike conventional pickups for electric guitars, hexaphonic pickups generate a separate signal for each guitar string instead of a single combined signal for all six strings. This simplifies the task to convert analog guitar signals to the prevalent MIDI format for music notation and communication between digital music instruments and control devices.

The conversion of audio signals to musical notation such as C, $D^{\#}$, E^{b}, and so on is typically based on digital signal processing methods or on specifically trained neural networks. The analysis seeks to detect the fundamental frequency or "pitch" of the perceived tone heights. State-of-the-art approaches can analyze so-called monophonic signals with only one predominant tone at a time. However, they fail to reliably detect multiple notes of polyphonic signals such as guitar chords where several tones are played simultaneously.

In this context, a hexaphonic pickup for electric guitars together with a complete hardware and software processing chain from sound generation to pitch detection has been developed (Fig. 1). A first functional, but mechanically instable, pickup was used to record soundtracks representing individual strings to audio files. These files were analyzed and successfully converted to the MIDI format [1]. In parallel, the initial design and manufacturing process of the pickup was improved.

The work serves as proof of concept that monophonic pitch detection can work quasi-polyphonic when using hexaphonic pickups. Moreover, the pickup and principal audio chain provide a solid platform for future works in the fields of, for instance, computer science, electrical engineering, applications related to music, and in general classical signal processing as well as deep learning applied to parallel time signals.

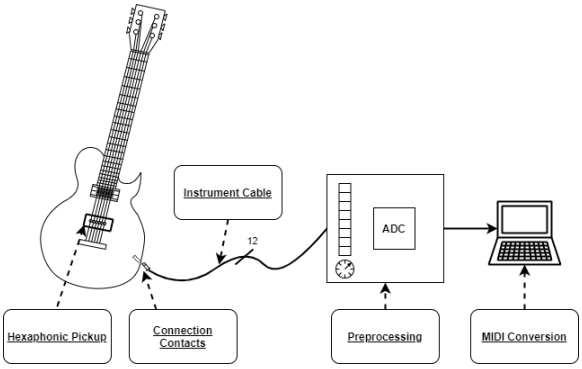

Fig. 1: Audio processing chain. In contrast to common pickups, a hexaphonic pickup generates six audio signals representing the guitar's six strings. The signals are transmitted, preprocessed, and sampled by an audio interface for further processing in a computer. Subsequent analysis converts the input into the MIDI format.

2 Hexaphonic pickup

Given the limited time and the larger number of topics to be addressed for the complete audio chain, the decision was taken to follow a two-step approach. First, construct a functional pickup within a short time frame, neglecting aspects like mechanical stability. This has put us in a position to record individual strings and work on the signal analysis without too much delay. Second, and in parallel, use the experiences made during the construction of the first prototype to develop a future-proof hexaphonic pickup.

2.1 Single coil vs. humbucker format

A fundamental design decision was the form factor, that is, the principal geometric shape and dimensions of the pickups. Once, these were fixed, all required parts are modeled in a CAD software and produced using a 3D printer.

As the pickups are mounted in common electric guitars, we concluded to follow the standard form factors of single coils or humbuckers. Humbuckers are roughly twice the width of single coil pickups. This allows to place the six coils alternately shifted along the strings, meaning coils can have larger diameters, more windings, and consequently output higher signal strength. However, it was unclear if the higher output is needed and coils with larger diameter may be more sensitive to signal induced by neighboring strings.

Moreover, the single coil format is more flexible as many guitars do not offer the larger humbucker slots. Hence, single coils could be mounted in a wide range of guitars without modifications of the wooden corpus. Initially, it was also unclear how much space is needed

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for the electrical connections because wires for six coils instead of one must be provided.

Considering these aspects, it has been decided to build the pickups in single coil format but mount them in humbucker slots, which provide enough space for additional wiring and electronics.

2.2 Electric guitar

The next decisions to be considered were which type of electric guitar to select and where to mount the pickup in the guitar. Pickup dimensions are slightly different for, say, Telecaster or Stratocaster models. Moreover, the distances between strings, and thus the magnets, differ at the neck, middle, and bridge positions.

Finally, a guitar of the Harley Benton SC-200 BK Student series was purchased. The main reasons were that this low-cost instrument fitted the budget for student theses, and it contains large humbucker slots at the neck as well as the bridge. This gives the flexibility to mount our pickup at both positions.

Additionally, there is a private Stratocaster-like guitar Aria Pro II Cat Series, which may be used as further instrument in future. The guitar features a humbucker slot at the bridge, while the pickups at the neck and in the middle position are in single coil format.

2.3 Bridge vs. neck position

The decision was taken to use the neck position of the Harley Benton guitar for the experiments. Each coil of a hexaphonic pickup has less space and will have less windings than the single large coil of a traditional monophonic pickup. Consequently, one expects less electromagnetic induction and lower signal strength, which is a potential challenge. In comparison, the amplitudes of string oscillations and therefore induced electrical signals are larger at the neck than near the bridge, where the strings are mechanically fixed.

Nonetheless, if signal strengths are sufficient, it will be interesting to experiment with the bridge position as well. Smaller amplitudes of string oscillations may reduce unwanted induction of neighboring strings. Moreover, wires and cables attached near the bridge will most likely disturb musicians using the instrument far less. And finally, musicians may prefer the softer sound of a traditional pickup near the neck, while they use the hexaphonic pickup near the bridge for audio signal processing, only.

2.4 Prototype for audio analysis

Based on above principal design decisions, a housing with six circular coil recesses was modeled and 3D-printed. Each coil was wound in a laborious process from 0.08 mm thick enameled copper wire around an Alnico 5 magnet mounted on a stepper motor. The resulting coils had about 2,000 windings each, and an electrical resistance of about 135 Ω.

Fig. 2: First prototype. The pickup was mounted in a humbucker slot at the guitar's neck position. In contrast to single coil slots, the humbucker format offers sufficient space for electrical components. Compared to the bridge position, string oscillations are larger at the neck, resulting in larger signal strengths.

The coils were placed in the housing and the recesses filled with heated fluid wax to encapsulate the coils in the housing and reduce microphonic effects due to slight movements of the copper wires. Finally, electrical connections to instrument cables were established by contacts soldered on a breadboard.

Fig. 2 depicts the mounted pickup. Some of the extremely thin copper wires broke during the manual manufacturing process, so that not all coils were functional. Nonetheless, the pickup could be used to record signals of several strings, including the neighboring strings E (6th) and A (5th). As described in Section 3, the recorded audio files were further processed on a laptop.

However, manufacturing the pickup proved to be difficult and the resulting component was mechanically unstable. Therefore, both the design and the manufacturing process have been significantly improved, taking the insights gained into account. Among other things, and as presented in the next sections, 3D-printed cores for the coils, a device for winding the coils, and a printed circuit board as an electrically and mechanically stable enclosure of the housing were developed.

2.5 Housing design

First experiments indicated that the signal strength at the neck is sufficient for subsequent signal analysis, while disturbances from neighboring strings were observed. Hence, the housing design was adapted for single coil pickups mounted at the bridge position of S-type (i.e., Stratocaster-like) guitars.

Fig. 3 and 4 depict the form factor and the CAD model of the housing. Noteworthy, there are two types of recesses that traditional pickups do not contain.

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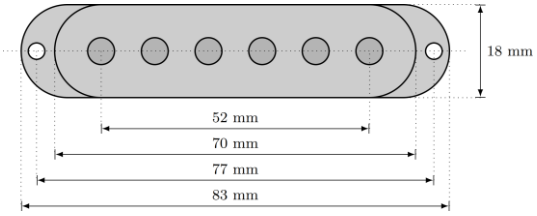
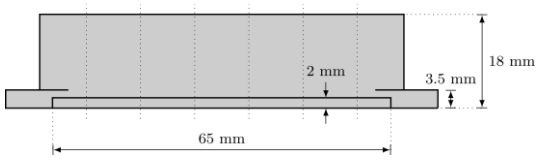


(a) Top view



(b) Side view

Fig. 3: Housing dimensions. The pickup is designed for the bridge position of S-type guitar models. The housing holds commonly used magnets with a diameter of 5 mm and 18 mm length and can be mounted with two M3 screws. The bottom contains a gap of 2 mm height, which is required for the printed circuit board.

As shown in Fig. 3(b), there is a small gap at the housing's bottom. This space is required for a specifically designed printed circuit board, to be discussed in Section 2.7. Moreover, there are six elliptical recesses to hold the coils (Fig. 4). The elliptical shape fits the top and bottom of the 3D-printed coil holders as discussed in Section 2.6.

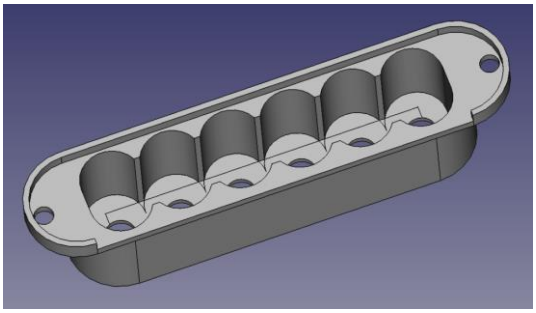


Fig. 4: Housing CAD model. The housing contains six deep elliptical recesses for the coils and a shallow recess to hold the printed circuit board, which provides the electrical connections and serves as stable cover at the bottom of the pickup.

2.6 Coils and winding device

The coil holder depicted in Fig. 5 has been designed for mechanical stability of the coils during and after production. The holder features a cylindrical hole to hold the magnetic kernel as well as thin walls at the sides. The walls simplify the process of winding the copper wire and give mechanical support. The two larger holes at the top and bottom have a diameter of 1.75 mm and can hold the signal ("hot") end of the wire, being inside the coil. The four smaller holes have a diameter of 1.25 mm and can hold the wire's ground, being at the surface of the coils.

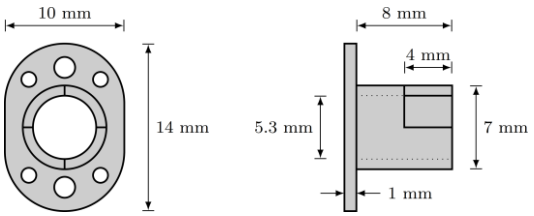


Fig. 5: Coil holder design. Each coil is wound around two 3D-printed parts with a magnet as core (see also Fig. 6). The two ends of the copper wire leave the coil's interior through the smaller holes.

Winding is done in a semi-automatic way by the device shown in Fig. 6. Basically, it consists of a clamping mechanism for the coil holder, a stepper motor to turn the coil holder, motor driver and Arduino board for low-level operation of the motor, and a Python application running on a connected computer to control the process. The application lets users control the turning direction and speed, and it counts the number of windings. Left or right movements of wire are not done automatically. However, this can easily be controlled by manually guiding the wire between the two mechanical limiters at the left and right.

As final production step, coils are sealed with wax to fixate the windings and reduce microphonic disturbances. For this, coils are put into fluid wax heated to about 77° C until no air bubbles emerge from the coils anymore. The resulting coils each contain about 2,000 turns and have an electrical resistance of approximately 170 Ω.

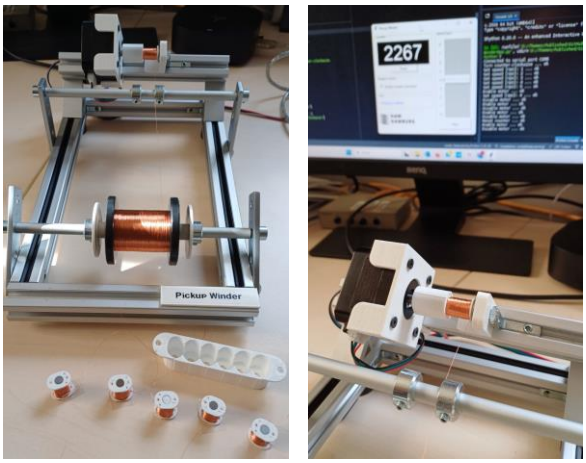


Fig. 6: Pickup winder. Coil holders are clamped in and turned by a stepper motor. The graphical user interface of the related application controls direction and turning speed and counts windings.

2.7 Printed circuit board (PCB)

A printed circuit board (PCB) acts as stable mechanical seal of the housing and provides electrical connections. Noteworthy and different to the first

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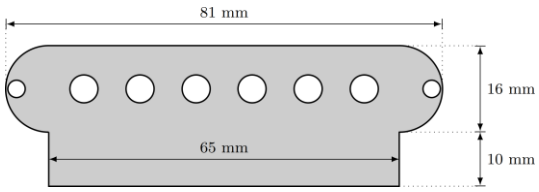
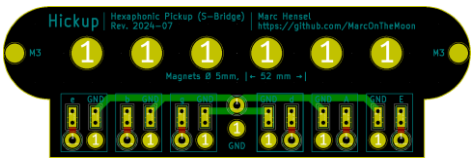


(a) Dimensions



(b) Electrical design

Fig. 7: Printed circuit board design showing the (a) geometric dimensions and (b) electrical traces. The board mechanically seals the pickup and provides electrical connections to the six coils with six "hot ends" and a common ground connection.

prototype, the design in Fig. 7 combines one end of each coil to a common ground. This reduces the number of electrical wires from 12 (signal and ground of 6 coils) to 7 (signal of 6 coils and 1 ground). Moreover, each electric pad for the coils' wires contains two small holes. This design allows to thread the extremely thin wires through the pads several times, which makes soldering easier and adds to the stability of the electrical connection.

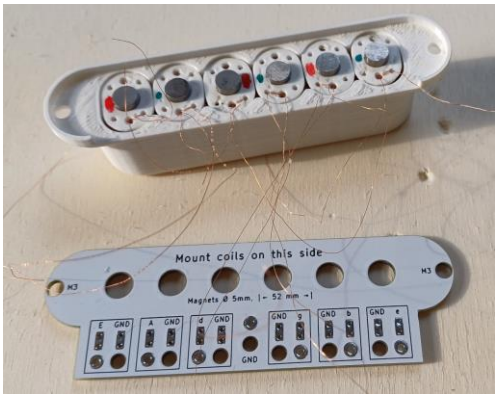
2.8 Assembly and connections

Pickup assembly is straight-forward (Fig. 8). The prepared coils were inserted, and the PCB was placed in the recess at the bottom of the housing. Naturally, care had to be taken that the extremely thin wires do not break. Finally, the wires were threaded through the pads with the help of tweezers and soldered on the PCB, establishing the electrical contact.

For the connection of the guitar, a 7-pin XLR cable and an adapter box, which splits the input to six instrument cables, were produced. The instrument cables are fed into a USB audio interface Behringer U-Phoria UMC1820 connected to a laptop (Fig. 9). This model was selected because it provides enough input channels accepting instrument level signals for all six strings.

3 Pitch detection and MIDI conversion

As indicated in Section 2.4, a first pickup prototype was developed to record sounds and start working on the signal processing already in an early phase of the project. For the analysis, the "deep" strings E (6th) and A (5th) were used for two simple reasons. First, these are the thickest strings, meaning they most likely induce strong sound signals in the corresponding and the neighboring coils. Secondly, their respective coils



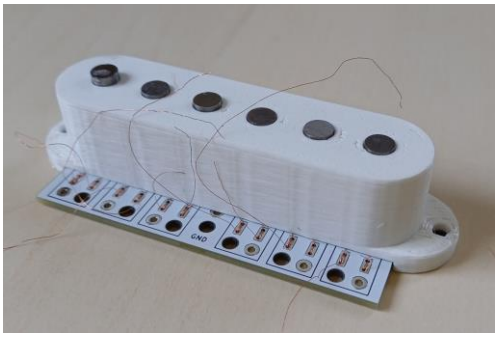


Fig. 8: Pickup assembly. Mechanically, insert the coils in alternating magnetic polarity and direction of winding, and clip the PCB into the housing. Electrically, thread the thin coil wires through a pair of holes in the corresponding pad and solder them at the bottom of the pickup.

Fig. 9: Adapter box and audio interface. The box splits six signal wires and the common ground to six standard instrument cables. These are input to the audio interface connected to a standard laptop.

survived the error-prone manufacturing process and were functional.

3.1 Audio recordings

For the subsequent analysis, several audio sequences were recorded and saved to Waveform Audio File Format (WAV) files. The recordings contain single tones, series of different tones played on the same string, and melodies using the E and A string. The speed ranges from long, fading notes to eights notes at 120 beats per minute.

3.2 Pitch detection

A principal approach to detect fundamental frequencies in a discrete time series x_t is by using autocorrelation, which measures the similarities when the data is shifted by τ discrete time steps, for instance,

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$$r_t(\tau) = \sum_{j=t}^{t+T-1} x_j \cdot x_{j+\tau} \quad (1)$$

with shift τ and window T. If a series is periodic with a given frequency, autocorrelation shows local maxima where the data of the original and shifted series match.

For our experiments, a similar approach was applied, the so-called YIN algorithm [2], which typically has a better performance for pitch detection. In contrast to autocorrelation, the method does not rely upon maximum products but minimum differences:

$$d_t(\tau) = \sum_{j=t}^{t+T-1} \left(x_j - x_{j+\tau}\right)^2 \quad (2)$$

3.3 Preliminary results

The main objective of the work so far was to develop an audio chain from hexaphonic pickup to converted MIDI files. This shall serve as a proof of concept and foundation for future work. Hence, we did not generate and statistically evaluate thousands of audio samples.

However, the experiments have shown that applied to our data, YIN typically succeeded to identify pitches as well as tone lengths correctly. Fig. 10 exemplarily shows the results for a series of quarter tones played on the E string. Although the quality could be further improved by postprocessing of the data, the identified fundamental frequencies in the top plot typically match the expected frequencies quite well. More samples along with a detailed discussion are provided in [1].

Occasionally, pitch errors in the sense that a tone was identified in the wrong octave were observed. In Fig. 10 such an error occurs when changing notes after about 6 seconds. Moreover, potential issues were identified for soft tones, fading tones, and soft disturbances from neighboring strings. All of this was to be expected and should be addressed in future works by postprocessing.

3.4 MIDI conversion

Once the pitch and length of each played note have been determined, writing the musical data to a MIDI file is no problem. For details on the file format and our implementation refer to the original standard [3] or the thesis [1].

A corresponding MIDI file has been created for each recorded audio sample. Again, we did a proof of concept rather than a statistical evaluation of thousands of audio tracks. In this context, the results were qualitatively verified by opening the files in a MIDI editor software. As expected from the analysis in Section 3.3, in principle the MIDI files corresponded to the notes played on the guitar. Although there are artifacts like short gaps in notes, we are confident that these can be addressed by postprocessing in future works.

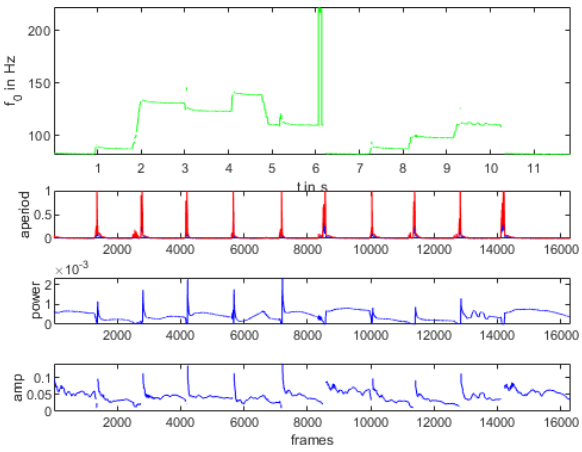

Fig. 10: Analysis for quarter tones played on the E string (6th). The identified fundamental frequencies in the top plot mostly match the expected frequencies. The narrow peak after about 6 seconds is a pitch error during a change of tone.

Summary

In this work a complete audio processing chain has been elaborated, which individually picks up and processes the sounds of all six strings of an electric guitar. This included an initial as well as a largely improved design of a hexaphonic pickup, pitch detection analysis, and conversion of detected tone heights and durations to MIDI files.

Outlook

This work can serve as foundation for future works in various applicational and technological fields. This includes, but is not limited to, improved pickups, pitch analysis by classical signal processing and deep learning, pitch analysis of chords, automatic music transcription, and live processing with low latency.

Acknowledgements

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