ACOUSTIC GUITAR PLUCKING POINT ESTIMATION IN REAL TIME

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ABSTRACT

The algorithm estimates the plucking point of guitar tones obtained with an undersaddle pickup. This problem is approached in the time domain by applying autocorrelation estimation. This work extends a recently developed algorithm and brings it to a practical and sufficiently robust level. Improvements have been made to the onset detection part of the algorithm. The algorithm also enables a new way to control, for example, audio effect parameters in real time by simply changing the plucking point. The paper discusses these issues and the real-time implementation in the Pd environment. In tests the real-time implementation achieved a 96 % hit rate while the estimation error remains smaller than one centimeter, except for a few outliers. Audio samples and a Pd implementation of the algorithm are available on-line at www.acoustics.hut.fi/demos/plucking-point/.

1. INTRODUCTION

One of the parameters controlling the spectral characteristics of a plucked string is the plucking point. The comb-like effect caused by the plucking point is well known [1]: the harmonics that have a node at the plucking point are not excited and ideally have zero amplitude.

Previously, a frequency-domain based technique has successfully been used to determine the plucking point in guitar tones [2, 3]. In contrast, this algorithm approaches the problem from the time-domain by observing the short-time autocorrelation function. In [3], the autocorrelation function is used as an initial estimate for an iterative frequency-domain method.

The work presented here extends our previous research. In [4], we proposed a plucking point estimation (PPE) algorithm that determines the plucking point of a guitar tone based on the autocorrelation function of one period of a guitar tone. An advantage of examining only one period of the tone is that problems caused by nonlinear coupling of harmonics is avoided [5]. In addition, a crucial feature here is that the observed signal is obtained from a guitar pickup placed under the saddle of the instrument. In other words, the microphone is placed where the strings end. The pickup used in this study is a B-Band microphone made of Emfit(R) film [6] (Trademark of Emfit Ltd). This microphone captures a cleaner representation of the string vibrations than would be possible through air radiation. This is because the filtering effect of the soundbox and direct radiation from strings is practically missing in the undersaddle microphone [7].

In addition to real-time implementation, the progression compared to previous work is mainly in the onset detection procedure. The onset detection is made more robust for real-time purposes. This is accomplished by using a frequency dependent time-window to locate the exact onset event.

2. TIME-DOMAIN EFFECTS OF VARYING THE PLUCKING POINT

Next, we discuss the vibration of the string in the time-domain according to the traveling wave theory and, based on this, how the plucking point can be observed. When a string is plucked or struck, two transverse waves will travel in opposite directions reflecting back and forth between the boundaries. The reflecting waves or pulses form a standing wave on the string. The vibration of the string will decay and settle to its rest position, due to external and internal losses [1]. Ideally, the traveling waves, resulting from a pluck can be regarded as moving impulses. In addition, the reflections at the boundaries are assumed to be ideally rigid, resulting in a reflection coefficient of -1. Therefore, the phase of each impulse is inverted at the boundaries.

To exemplify the traveling impulses we look at Fig. 1. It shows the cross-sectional view along the string at three time instances ($t_0, t_1,$ and t_2) and the input at the bridge pickup, as a function of time. When $t = t_0$, the string has been deflected, but has not been released yet. When $t = t_1$, the impulse first traveling to the right, i_1, has reached the bridge. When $t = t_2$, the impulse first traveling to the left has reached the bridge.

To obtain an estimation of the plucking point the time difference between the first two incoming impulses i_1 and i_2 is to be calculated, as follows. The time for an impulse to travel from one end of the string to the other is

$$T_{1/2} = \frac{1}{f_0}\frac{1}{2}, \qquad (1)$$

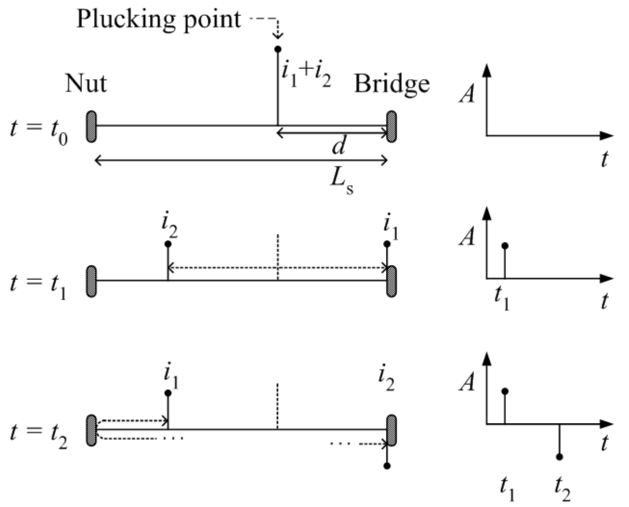

Fig. 1. Cross sectional view along the string at three time instances (on the left-hand side) and the corresponding input of the guitar pickup at the bridge as a function of time, after [4].

where f_0 is the fundamental frequency of the vibrating string and $T_{1/2}$ is half of the fundamental period. The time for impulses i_1 and i_2 to arrive at the bridge can, respectively, be expressed as

$$\tau_1 = \frac{d}{c} = \frac{d}{f_0 \lambda} = \frac{d}{2 f_0 L_s} \tag{2}$$

and

$$\tau_2 = 2T_{1/2} - \tau_1 = \frac{2L_s - d}{2 f_0 L_s}, \tag{3}$$

where $c = f_0 \lambda$, c is the velocity of the transverse wave, $\lambda = 2L_s$, L_s is the length of the string, d is the plucking point as the distance from the bridge, and λ is the wavelength of the string's fundamental. The plucking point can be solved through determining $\Delta\tau = \tau_2 - \tau_1$. In the discrete domain the plucking point as the distance from the bridge is

$$d = \frac{L_s(f_s - \Delta T f_0)}{f_0}, \tag{4}$$

where f_s is the sampling frequency. On these grounds, we can understand that it is sufficient to analyze only one period of the string vibration to the determine the plucking point. In the frequency domain, the first two pulses create a comb-filtering effect far denser than the one observed in the overall spectrum of a vibrating string [4].

3. PLUCKING POINT ALGORITHM

The plucking event of a guitar tone is quite well defined, compared to a bowed violin tone for example. This makes

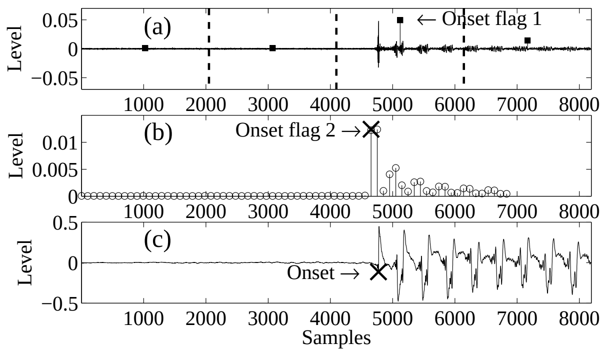

Fig. 2. (a) Highpass filtered signal waveform with energy of each frame marked with a square, (b) energy of highpass signal with the pitch-synchronous window, (c) and original signal and detected location of onset (x).

the task appear straightforward. However, the real problem is to define the exact moment when the first impulse of a pluck event arrives. Therefore, we use two frame lengths, a long one for the rough onset detection and a short, pitch-synchronous window, for the exact detection of the first impulse. Next the algorithm is discussed with the help of Figs. 2 and 3, which are example results of an open A-string plucked 16 cm from the bridge.

3.1. Rough onset detection

First the incoming signal is highpass filtered with an elliptic second-order IIR filter with a -3 dB point at 6 kHz. During a plucking event or the attack of a tone, the amount of high frequency components is larger than during the decay or steady state portion. Hence, the highpass filtering is done to clarify the signal and make the onset analysis easier. Then the energy is calculated from 2048-sample frames with a 50% overlap, i.e., almost 50 ms long frames when the sampling frequency is 44.1 kHz (as used in this study). An onset flag is set, if the energy increases tenfold in two consecutive frames. Fig. 2 (a) illustrates the highpass signal, the calculated energy in each frame, and the frame where the onset flag 1 is set on. The borders of the frames are indicated with vertical lines.

3.2. Fundamental frequency estimation

Then the fundamental frequency is estimated with the autocorrelation method [8]. For the autocorrelation method to work properly, at least 2 to 3 periods of the signal are needed. For a guitar, the lowest E note is about 82 Hz, which corresponds to about 540 samples per period. In this work, the fundamental frequency is estimated from 4 consecutive frames (8192 samples $\simeq$ 186 ms): the frame where the onset was detected, two previous frames, and the next one.

3.3. Exact onset detection and extraction of a single period

When the algorithm has observed a plucking event, one period of the signal is extracted. First, the exact moment of the pluck has to be defined. For this purpose pitch-synchronous analysis is used, with a window which is half the wavelength of the fundamental frequency of the signal. Similarly as for the rough onset detection, overlap between the frames is 50% and the onset flag is set when in two consecutive frames the value of energy is ten times larger than in the previous frame. These energy calculations are made for a highpass filtered signal. Fig. 2 (b) shows the energy of the highpass filtered signal calculated in the frequency dependent frames and the frame where the second onset flag is set on. After this, the maximum absolute value is searched from the 3 consecutive frames, of the original unfiltered signal. The starting point of the pluck is the last time the signal changes sign before the found maximum. One period is obtained by extracting a wavelength that corresponds with the fundamental frequency. Fig. 2 (c) depicts the original signal and indicates the exact onset location that was found.

3.4. Plucking point estimate

After these procedures, the autocorrelation function (ACF), as defined in, e.g., [8], is calculated for the extracted one period. The ACF compares this to its shifted copy, and for a periodic signal it shows positive peaks at multiples of the period. This is why the ACF is used for fundamental frequency estimation. In this application, the exact opposite quality is used in the following manner. The first pulses arriving at the guitar pickup are antisymmetric, i.e., negative to one another. In the ACF this will cause a strong negative correlation and will appear as a negative peak in the ACF. This is the crux of the matter, since the negative peak will show at a time lag corresponding to the plucking point d. To improve the accuracy of the estimation, parabolic interpolation can be used as in [4].

The plucking point estimate will be determined with the help of the negative peak of the ACF. The index of the minimum of the ACF corresponds to ΔT in (4). By normalizing the plucking point with string length the relative plucking point can be derived from (4) and is

$$d_{\mathrm{rpp}} = \frac{\Delta T f_0}{f_{\mathrm{s}}}. \quad (5)$$

The actual plucking point measured from the bridge is obtained by multiplying d_{rpp} with the string length L_{s}. Fig. 3 shows the extracted single period and its autocorrelation function. For the example case used in Figs. 2 and 3 the algorithm yields the estimate 15.82 cm, when the actual plucking point was 16.00 cm.

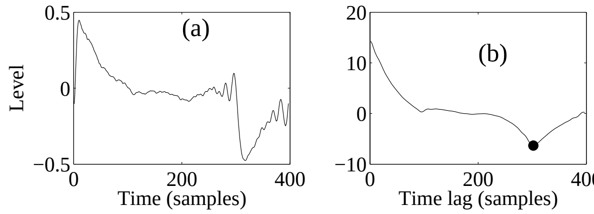

Fig. 3. (a) An extracted wavelength and (b) its autocorrelation function. The minimum of the ACF is marked with a dot.

4. IMPLEMENTATION

The algorithm was implemented using the Pd (Pure data) environment as a Pd external [9]. The external was written in C. Several parameters of the algorithm are user controllable. Users can control the *energy ratio* that the signal energy must increase in two consecutive frames, both for the rough and exact onset detection. The cutoff frequency of the highpass filter used in the rough onset detection can also be chosen, from 3 kHz, 6 kHz, and 10 kHz. Users can also control the *energy limit*, i.e., the energy level the input signal has to exceed in order for an onset to be detected. This limit is used to remove false onsets caused by guitar handling noises. It is also possible to limit how often an plucking point estimation is given (*output scheduler*). This is controlled by setting a tempo and number of beats per measure. This will control how much time must pass after one onset before a new onset is given.

The *output type* can also be chosen, between a continuous setup, which gives plucking point values, and a discrete on/off setup that outputs values 0 or 1 depending on the plucking point. The output of the plucking point estimator external can be used to control for example an audio effect. In this work the reverberation time of a reverb effect is controlled by altering the plucking point. The implementation also enables to control external MIDI-controllable effects. The Pd implementation, examples, and a manual are available on-line at www.acoustics.hut.fi/demos/plucking-point.

5. RESULTS

To test the algorithm in real-time, a collection of guitar tones were recorded and played back from a CD player to the system. The collection of plucks consisted of plucking points from 2 to 32 cm on each open string, with four repetitions of each pluck, i.e., a data base of 384 plucking samples was gathered. This collection of plucks was fed to the real-time system, which consisted of an PC with an Intel Pentium 3 1 GHz processor with 768 M of RAM and an M-Audio Audiophile 2496 soundcard, used in the Windows 2000 operating system. The CD player was connected to the soundcard

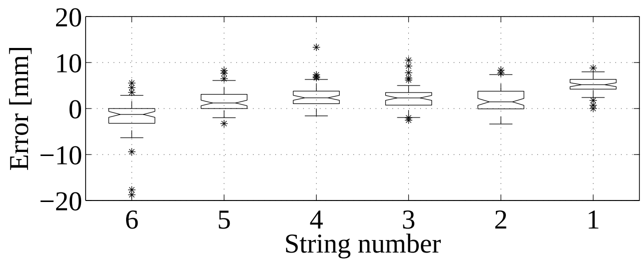

Fig. 4. Plucking point estimation results for the real-time system. The y axis indicates the estimation error and the x axis indicates the string, so that 6 is the lowest and 1 the highest string on the guitar.

via a Fostex Model 812 mixer.

Fig. 4 displays the results, so that the estimation error is indicated on the x axis and the y axis indicates the string number of the guitar. A few (20 samples) gross outliers are outside the figure. In the figure, each box has lines at the upper (75 %) and lower (25%) quartile values. The median value is indicated between these values with a transversal line in the hour-glass shaped part of each box. The whiskers (| - - - |) show the extent of the rest of the data. Outliers, displayed with the star symbol (*), are data points with values beyond the end of the whiskers.

The real-time implementation of the algorithm attained a hitrate of 96.0 %, out of which 93.2 % are within one centimeter of the target plucking point. All the median values are within 5.2 mm of a 0 mm error. These results were obtained with the following parameter values: rough onset energy ratio = 10, exact onset energy ratio = 8, energy limit = 50, and f_c = 6 kHz for the highpass filter.

Problems and errors occur in the following cases. When the string hits a fret an additional pulse is generated which prevents the algorithm to work properly. When the pluck is executed with a soft plectrum, finger, or finger and nail the waveform is difficult to analyze. This is due to interactions between the string and the initiator and the finite width of the plucking point, which causes the vibration to have lowpass filter characteristics. Plucking continuously and quickly also causes difficulties in identifying the plucks properly.

6. DISCUSSION AND CONCLUSIONS

The plucking position in itself changes the timbre of the string's tone, most notably the brightness. This effect is used as an expressive tool in music. By using the PPE algorithm to control an audio effect, changes in the plucking position can affect the timbre even more dramatically than in the natural unprocessed case.

The PPE algorithm can also be applied to an electric guitar, because the magnetic pickup signal does not contain the direct radiation of the strings nor effects of the soundbox, which can lead to estimation difficulties. However, the positioning of the magnetic pickup can cause some trouble.

The proposed and discussed plucking point estimation algorithm works in real time and is a useful ”Look! No feet” way to control musical applications.

7. ACKNOWLEDGEMENTS

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