A Left Hand Gesture Caption System for Guitar Based on Capacitive Sensors

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ABSTRACT

In this paper, we present our research on the acquisition of gesture information for the study of the expressiveness in guitar performances. For that purpose, we design a sensor system which is able to gather the movements from left hand fingers. Our effort is focused on a design that is (1) non-intrusive to the performer and (2) able to detect from strong movements of the left hand to subtle movements of the fingers. The proposed system is based on capacitive sensors mounted on the fingerboard of the guitar. We present the setup of the sensor system and analyze its response to several finger movements.

Keywords

Guitar; Gesture acquisition; Capacitive sensors

1. INTRODUCTION

The guitar is one of the most popular instruments in western culture. Its study is a very active topic in different disciplines like acoustics, organology, or signal processing [5, 12]. These studies provide valuable physical and gesture information from vibratos, slurs, plucking style or dynamic variations [4]. Nevertheless, the essence of guitar music is sometimes reflected by subtile particularities which are completely dependent on the players, styles, or musical genres. In other words, the richness of the guitar expressivity raises a challenge that, even analyzing each string individually (for instance using hexaphonic pickups), it is still partially tackled. A possible approach to overcome these issues is to enhance the (sound) information captured from the guitar by acquiring gesture information.

The study of performer gestures in music is not new. For instance, Young [14] presented a system to capture the performance parameters in violin playing. Focusing on the guitar, there are some interesting approaches studying the gestures of guitar players [8, 13]. Gestural information related to guitarists may refer from movements of the guitar body, to the detailed study of specific finger movements. In our case, we are interested in the study of the finger gestures of the left hand. Such information may be useful for studies ranging from the analysis of specific performers to the identification of nuances in guitar solos.

Centering on the finger movements, the available approaches are traditionally based on the analysis of images: Burns [2, 3] proposed a method to visually detect and recognize fingering gestures of the left hand of a guitarist. Heijink [6] proposed the use of a three-dimensional motion tracking system (Optotrak 3020) to analyze the behavior of the left hand in a classical guitar. Norton [10] proposed the use of another optical motion caption system based on the Phase Space Inc., with quite successful results. Although these systems provide valuable data, we advocate that it is better to acquire gesture data as close as possible to the fingers instead of using indirect techniques, even with the good results they provide. In fact, the information from both (optical and capacitive) sensor systems can be complementary.

The goal of this paper is to propose a sensing system that allows the study of the gestures of the left hand fingers in guitar performances. This system has to be able to capture from *macro-scale* changes (i.e. the presence of finger bars) to *micro-scale* changes (i.e. vibrato) in player's movements. Furthermore, the sensors have to be non-intrusive to the player. The paper is organized as follows: First, in Section 2 argue and explain the approach we are using. Then, Section 3 presents the setup of the system and summarizes a set of static measurements such as background noise, sampling frequency, and crosstalk. Next, in Section 4, we detail all the experiments we made to analyze the sensor's behavior from *macro-scale* to *micro-scale*. Finally, we summarize the experimental results achieved by the sensor system in Section 5.

2. CAPACITIVE SENSORS

As mentioned previously, most of the existing proposals for left hand gesture caption are based on optical or image techniques. Although these systems have proved to provide successful results, under our point of view, either they are expensive or a bit intrusive to the performer, in terms of a reduced mobility in live environments. On the other hand, after observing several guitar players, we realized that the fingers do not perform a big pressure on the fingerboard, and even, do not necessarily touch the fingerboard (specially in high pitches). Then, what we need is a distance sensor that measures the distance between the fretboard and the fingers, and capacitive sensors perfectly accomplish all these requirements.

Capacitive sensors are not new in music. The Theremin, invented in 1919 by Lev Termen, is considered the first electronic instrument in the history. It is based on the capacitive effect of a player near two antennas, one controlling the pitch and the other controlling the loudness. More recently, new musical interfaces and augmented instruments use also capacitive sensors to control musical parameters [11, 7].

NIME2010, June 15-18, 2010, Sydney, Australia

Technically speaking, capacitive sensing is based on the change of capacitance of two conductive electrodes in a dielectric. The capacitance is the ratio of electric charge over a voltage:

$$C = \frac{q}{V} \tag{1}$$

where C is the capacitance in Farads $[F]$, q is the charge in Coulombs $[Q]$, and V is voltage in Volts $[V]$.

The capacitance of an ideal capacitor built up with two conductive parallel plates is computed as:

$$C = \varepsilon_0 \varepsilon_r \frac{S}{d} \tag{2}$$

where ε_0 is the vacuum permittivity ($8.85 \times 10^{-12}[F/m]$), ε_r is the relative permittivity of the medium (1.0005 for the air, adimensional), d is the distance between the two plates in $[m]$, and S is the plate area in $[m^2]$.

When using capacitors as sensors, their capacity inversely changes on the distance between the electrodes. But in our configuration, we use the *load mode*defined by Miranda [9] in which the distance between the electrode and a single object (the performer's finger in our case) is measured through a change in capacitance of the electrode to ground. There are different options to build capacitive sensors and their control unit. Home made sensors are useful for very specific applications, but their use is not recommended because of the electrical problems may appear (background noise, stability, robustness to interferences, etc.). CapToolKit[1] is a hardware and software toolkit for prototyping capacitive sensing systems. It consists of a control unit and a set of capacitive sensors, and the software implementing the protocol to communicate with your computer. Capsense[2] is a capacitive sensing library for Arduino. Arduino is a widely used open-source electronics prototyping platform that appropriate to our requirements. Specifically, Capsense is a library that converts the Arduino digital pins into capacitive sensors that are used to sense the electrical capacitance of the human body. Moreover, in our work we use this last option because it allows to combine the acquisition using capacitive sensors with other analog sensors (not included in this paper) using the same platform.

3. SETUP

The aim of our sensing system is to acquire gestural information from the left hand movements. For that purpose, an array of capacitive sensors was mounted on the fretboard of the guitar. These sensors provide information relative to the presence of fingers into that specific fret. Specifically, depending on the number of fingers present in a given fret, the position of these fingers, and the pressure of the fingers to the strings, the response of the sensors differ.

The two electrodes of the capacitor consist on an aluminum foil and the player's finger. In fact, the player's finger is not an electrode, but it is able to modify the electromagnetic field generated by the aluminum foil. The dielectric is achieved by using adhesive tape. Aluminum foils provide a capacitive value proportional to the distance between the player's finger and the foil itself, depending on the active surface (notice that, in real guitar playing, the fingers do not necessarily touch the fingerboard, specially in high pitches). Since the response of the sensors is also influenced by the area, different finger positions can be detected. The main advantage of using this technique is that it is not intrusive neither to the player nor to the recorded sound (See Figure 1 for details).

Figure 1: Non intrusive capacitive sensors mounted on the first 10 frets of a nylon guitar. The Arduino is attached to the guitar's body to reduce background noise and increase stability.

As mentioned above, we use the Capsense library for Arduino. The diagram of the whole gesture acquisition environment is shown in Figure 2.

3.1 Noise, stability, and sampling rate

According to the literature, capacitive sensors with small capacitive electrodes can be noisy and unstable[1]. Capacitive-based sensor systems explained in Section 2 propose some solutions to provide stability and noise reduction at the same time they provide an acceptable sampling rate. These solutions can be referred to hardware (modification of the resistor's value) or software (adaptive low pass filtering, sampling rate, etc.). In our case, we experimentally set the resistor's value to $R = 4.7M\Omega$ (R_1 to R_{10} in Figure 2), the maximum sampling rate to $\tau_{max} = 100[ms]$ and a low pass filtering with a fixed length of $L = 5$ samples.

In the configuration we chose (i.e. using the Arduino), the sampling rate depends on the measured value. Moreover, the sampling rate also depends on the number of used sensors. In consequence, the sampling rate is not constant. We converted measured data to MIDI, using PitchBend messages to provide enough resolution. MIDI data is automatically synchronized with the audio using a sequencer.

Beyond that, it is important to keep the control unit close to the sensors to avoid an important increase in the background noise and a high decrease of stability and sampling rate. Our first prototype was mounted near the computer with long cables to the sensors (about 5 meters). This setup provided a mean background noise for all the frets about 35 relative capacitance units $[rcu]$, and a sampling rate about $15[Hz]$. In our second prototype, the control unit was mounted on the guitar, as shown in Figure 1, obtaining a mean background noise for all the frets about $2[rcu]$ and a sampling rate about $35[Hz]$. These measurements have been made under the same hardware and software conditions and averaged on different setups using 10,5,3 and 1 capacitive sensors, to avoid the dependence on the number of used sensors.

Finally, by maintaining the control unit near the sensors,

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[1] http://www.capsense.org/

[2] http://www.arduino.cc/playground/Main/CapSense

Art.	Measured	2	3	4	5	6	7	8	9
Bars	Fret -1	48.0%	35.9%	31.1%	29.2%	27.7%	31.6%	32.9%	30.6
Bars	Fret +1	31.9%	28.9%	27.9%	27.3%	30.3%	28.9%	28.3%	34.3
s6	Fret -1	60.5%	53.1%	53.1%	51.9%	54.8%	51.8%	59.6%	51.2
s6	Fret +1	39.2%	46.3%	43.2%	46.9%	47.3%	43.5%	46.6%	56.7
s1	Fret -1	52.0%	42.0%	41.6%	36.9%	30.0%	36.3%	39.5%	36.6
s1	Fret +1	36.4%	37.4%	38.9%	37.2%	34.8%	34.1%	37.0%	46.9

Table 1: Percentages of the measured relative capacitance from previous and forthcoming frets, while playing bars, 6th, and 1st strings, from frets 2 to 9.

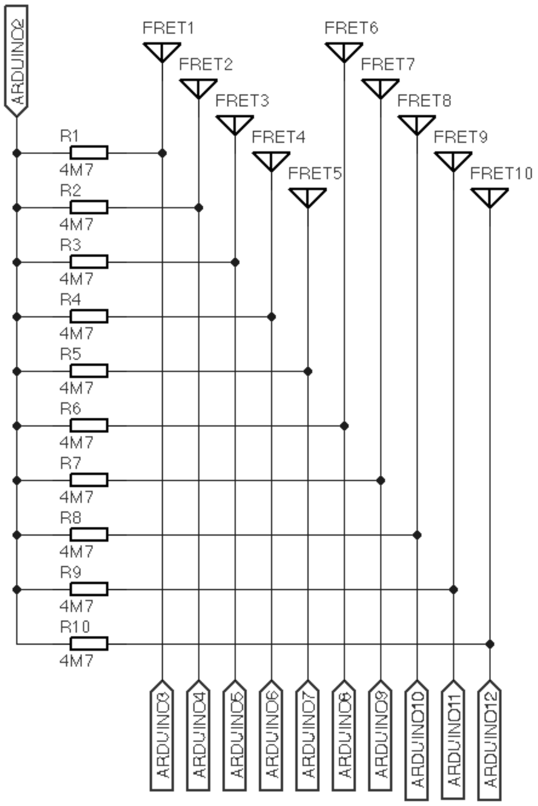

Figure 2: Diagram of the gesture acquisition system. The Arduino digital output 2 sends data to all the aluminum foils, and the relative capacitance is individually measured at arduino digital inputs from 3 to 12.

we avoid unexpected jumps in the background noise values in a long performance recording, that is, we increased the stability of the system.

3.2 Crosstalk

As explained in Section 3, capacitive sensors capture the distance between the aluminum foil and the fingers. In real guitar performances, the fingers and the rest of the hand are quite close one each other and may affect to many sensors. In addition to that, capacitive sensor platforms with multiple sensors generate some degree of dependency between data received from different sensors.

We measured and quantified this crosstalk from each fret with respect to the previous and the forthcoming ones, in three different scenarios: (1) playing bars from frets 2 to 9, in which the whole finger is acting to the whole sensor, (2) playing on the 6th string from frets 2 to 9, in which the whole finger is over the sensor but only the tip is really acting, and (3) playing on the 1st string from frets 2 to 9, in which only the fingertip is over and acting to the sensor.

Results of this measurement (see Table 1) show a crosstalk about a 30% to 50% of the target value, which is not negligible. Nevertheless, the difference is always significant (e.g. for the measurements of finger bars we obtain a difference of, at least, $200[rcu]$ whereas pressing single strings the difference achieves $80[rcu]$). In summary, crosstalk is not crucial but needs to be taken into account when analyzing forthcoming results.

4. EXPERIMENTS

In this section, we analyze the data acquired by capacitive sensors when different gestural movements are performed. We start studying gestures at macro-scale. Next, we proceed with the study at micro-scale gesture level by analyzing the response of the sensors to different musical articulations.

The first experiment studies the response of the sensors when the hand moves through the fingerboard, from the nut to the body of the guitar, whereas a finger is pressing all the strings in a given fret (finger bars). Next, we analyze the response of the sensors when performing chromatic scales over the same string, i.e. the finger moves through the fingerboard but the hand is more free than the previous case. Third, we study a specific case of chromatic movement: the grace notes. Grace notes are, in terms of gesture, small excerpts of a chromatic scale played too fast.

After analyzing the response of the system when acting over the same string, the following experiments are conducted to study the response of the sensors when the position of the left hand is fixed and the fingers are pressing different strings at different frets. Specifically, first recordings are performed by playing a diatonic scale. Next, following with the multiple strings analysis, we present the study of basic arpeggios in order to detect whether the caption system is able to deal with different (near to static) hand positions. In this experiment, we combine gestures observed in the analysis of fret bars and diatonic scales.

Additionally, we study a specific case of a gesture where the left hand plays the main role: hammer-on and hammer-off. In this gesture, a finger is pressing a string in a given fret whereas another finger presses and depresses the same string in an upper fret.

Finally, we analyze vibrato. Vibratos are achieved by fast and short horizontal movements of a finger that produce frequency oscillations. Notice that, in vibratos, the fingers do not change neither the fret nor the string. Thus, the purpose of this experiment is to analyze how this finger oscillations are captured by the sensors.

4.1 Finger Bars

As mentioned in Section 3.2, finger bars present the maximum contact area between the finger and the sensor. Then, the detection of the presence of a bar should be an easy task. For this recording, all strings are pressed by a finger, starting at the first fret; then, ascending fret by fret until the

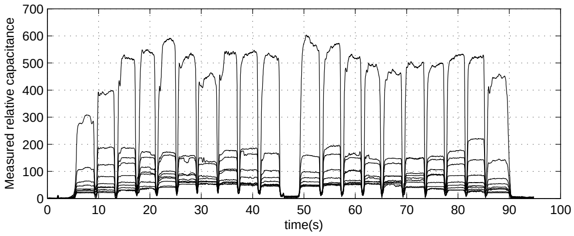

Figure 3: Relative capacitance for ascending and descending bar positions from frets 1 to 10 and 10 to 1. High values correspond to the targeted frets, and low values correspond to the other ones.

10th fret; next a pause of a beat; and finally, going down to the first fret. The change of fret occurs every 4 beats at $60[bpm]$.

Results (see Figure 3) show values ranging from 450 to $600[rcu]$ at the identified frets, and lower values in their neighbors, as explained in Section 3.2. As a conclusion of this experiment, we state that it is relatively easy to detect the presence of a bar using capacitive sensors.

4.2 Chromatic scales

Next, we record a set of chromatic scales, one for each string, starting with the open string and playing an ascending scale until the 10th. fret. The change of fret occurs every 4 beats at $60[bpm]$. Results (see Figure 4) show values about $200[rcu]$, about 50% less than the previous experiment. This result was expected because, in the chromatic scales, although the active surface between the finger and the sensor can be the same (e.g. the case when playing 6th string), the finger is more distant to the fret and the measured capacitance is lower.

Nevertheless, the measured values are still big enough to detect which fret is pressed in all the recordings with respect to the background noise and the crosstalk values from the neighbors. Furthermore, there are no significative differences between de recorded data provided by the sensors for the different strings. As a conclusion of this experiment, we state that it is relatively easy to detect the fret which is pressed while playing a monophonic melody.

4.3 Grace notes

As shown in the previous section, there are no relevant differences in the behavior of the acquired data from capacitive sensors for different strings. Then, for simplicity, experiments with grace notes are restricted to the first 3 stings. We conducted two different experiments: ascending and descending grace notes. Ascending grace notes start at the second fret, playing with an ascending grace note from the previous fret until the 10th fret. In an analogous way, recordings of descending grace notes start at the 9th fret and continued to the 1st one. The change of fret occurs every 4 beats at $60[bpm]$.

Analyzing all the gathered data, grace notes are detected independently on the fret and the string where they occur. Specifically, grace notes follow the same pattern: a capacitance peak at the initial fret and a contiguous activation of the target fret, at the same time that the initial one decreases to the background level (but, as mentioned in Section 3.2, some crosstalk effect is appreciated). Moreover, results are equivalent for ascending and descending grace notes.

For instance, Figure 5 shows an example of the change in relative capacitance from the initial note (4th fret, with a short duration) and the target note (5th fret, one semitone over, with a longer duration). Although in this example grace note detection seem an affordable task, it is important to take into account that the sampling rate of the system is relatively low (about $35[Hz]$). Then, if grace notes are played too fast, the system can loose them.

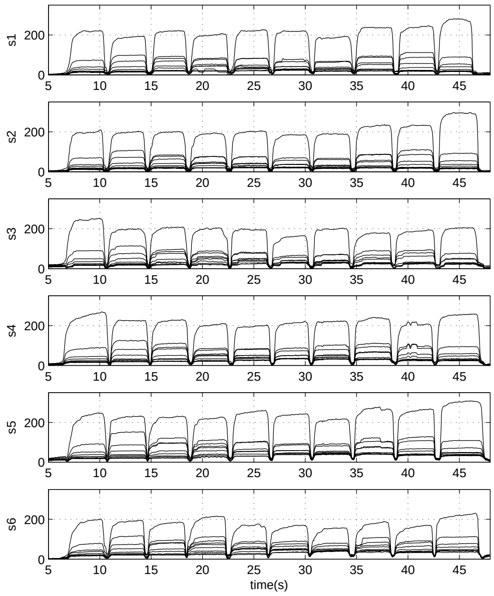

Figure 4: Relative capacitance for chromatic scales, for frets from 1 to 10, playing the 6 strings independently. High values correspond to the targeted frets, and low values correspond to the other ones.

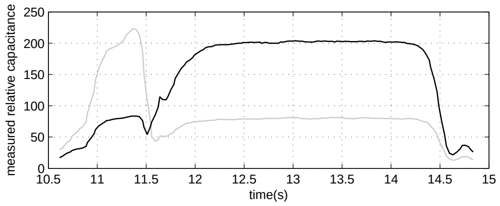

Figure 5: Relative capacitance for an ascending grace note between the 4th (gray) and 5th (black) fret at 1st string.

4.4 Diatonic scale

In opposition to the study of chromatic scales, shown in Section 4.2, we performed the study of major diatonic scales played at first position. In this scenario, the left hand and the fingers are static over the same consecutive frets and, depending on the note, one of the fingers presses one of the 6 strings at the assigned fret. There are no two fingers pressing at the same time. This experiment is closer to the movements of fingers in musical pieces.

The reported example corresponds to 2 octaves of a descending A major scale played at first position (see score and fingerings at Figure 6). The played frets follow the sequence: 5-4-7-5-7-6-4-7-6-4-7-5-4-7-5. The change of note occurs every beat at $60[bpm]$.

Results shown in Figure 7 show how the fret with maximum measured relative capacitance always corresponds to the target fret, i.e. we are able to detect the pressed fret. Moreover, close finger positions produce crosstalk interfer-

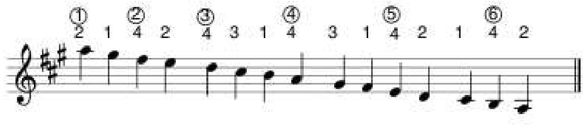

Figure 6: Strings (rounded numbers) and finger notation for a descending A major scale played at first position.

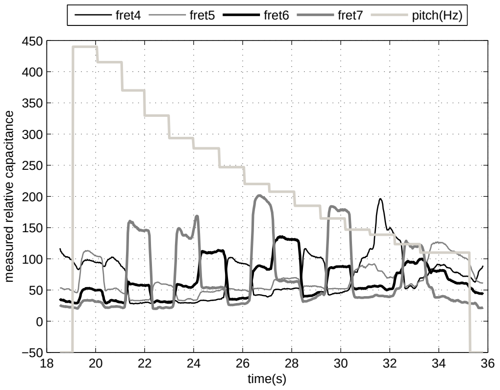

Figure 7: Measured relative capacitance for relevant frets during 2 octaves in a descendent A major scale, and the pitch estimation extracted from the audio. The active frets follow the sequence: 5-4-7-5-7-6-4-7-6-4-7-5-4-7-5.

ences between the measured value and the neighbor frets. For instance, at $t = 22[s]$, the 7th fret rises up to $150[rcu]$ at the same time that the 6th fret also increases its value about $25[rcu]$.

4.5 Basic Arpeggios

Let us study now whether the system is able to deal with different (near static) hand positions. We study the ability of capacitive sensors to discriminate between two hand positions playing the same arpeggio. The reported excerpt shown in Figure 8 was played at the first position (strings 3-2-1-1) and with a bar at the fifth fret (strings 4-3-2-2). The change of note occurs every beat at $60[bpm]$.

Results (see Figure 9) show, for the first position, finger pressure at frets 1 and 3 for the 2nd and 4th played notes, respectively. In the second one, the bar is detected at fret 5, while the finger at fret 8 is only detected for the last note (see the pitch information also included in the graph).

The measured relative capacitance differs depending on the used articulation. Bars provide highest values of relative capacitance and, as a residual effect, the relative capacitance from the neighbor frets is also affected. Nevertheless, the noise introduced by the bar does not prevent us to detect the finger pressure at fret 8, which is clearly above the residual noise when playing the 4th note.

In contrast, at the upper graph, the residual noise of the measured relative capacitance is near to zero while playing 1st and 3rd note. When pressing with the finger at the 1st and 3rd frets for the 2nd and 4th notes respectively, the residual noise is increased but, again, it does not prevent us to detect the fret which is pressed. Notice that, whatever the presence of a bar or the level of the background noise, the relative measured capacitance when pressing 1st or 2nd string for different frets is similar. This feature is important

Figure 8: Basic arpeggios played at different positions.

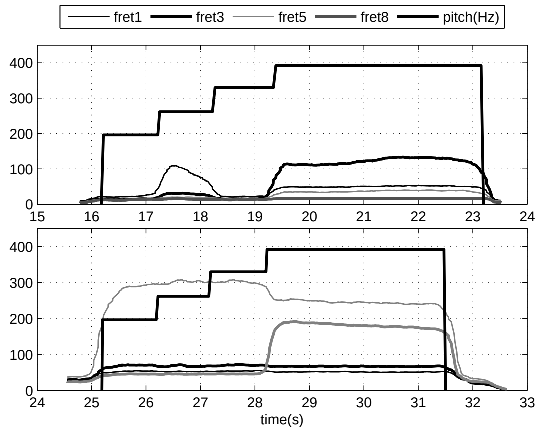

Figure 9: Measured relative capacitance for relevant frets during arpeggio playing, and the pitch estimation extracted from the audio. The upper graph corresponds to the performance at the first position. The lower one corresponds to the performance using the bar at the fifth fret.

for the recognition task.

4.6 Hammer on/off

The aim of this experiment is to study the behavior of the capacitive sensor system with multiple fingers acting simultaneously. For that, we study the behavior of the capacitive sensor system while playing hammer-on and hammer-off articulations. Specifically, we played a chromatic scale at $60[bpm]$, changing to the next semitone every 4 beats. We apply the hammer-on articulation at the beginning of the 2nd beat and the hammer-off at the beginning of the 3rd beat.

Hammer-on/off gestures are clearly captured by the capacitive sensor system. The presented pattern is a continuous activation of the fret where the fixed finger is located whereas a higher activation arises when the second finger acts. A crosstalk effect appears when both fingers are pressing the string, but it does not prevent a good gesture recognition.

For instance, Figure 10 shows an example of recorded gestures corresponding to the 8th fret and applying the hammer-on and hammer-off at the 9th fret, on the 3rd string. The 8th fret is clearly detected for the 1st, 3rd and 4th beats, while the 9th fret rises at the 2nd beat. We can also observe the effect of the crosstalk effect described in Section 3.2. The sensor system proposed in this paper is also able to detect hammer on articulations.

4.7 Vibrato

As in the previous cases, the study of vibrato was limited to the first 3 strings. Vibrato recordings are similar to those described for the chromatic scales in Section 4.2, starting at the first fret and playing an ascending scale until the 10th

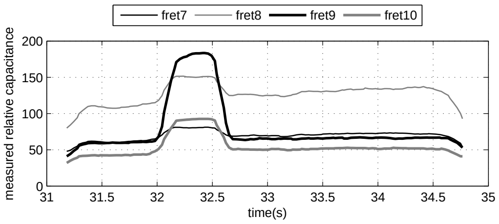

Figure 10: Measured relative capacitance for relevant frets playing at the 8th fret and applying the hammer-on and hammer-off at the 9th fret, on the 3rd string.

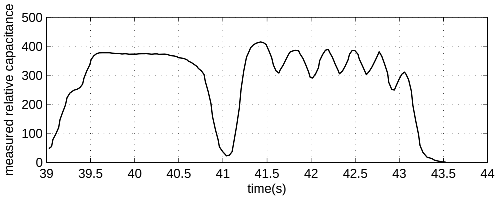

Figure 11: Relative capacitance for a 1st string and 10th fret. The first two beats are played without vibrato and, after a new attack given by the right hand, the note is played again but applying vibrato.

fret. The difference is that, in this experiment, each note is played twice: first, it is played normally and after 2 beats, it is repeated but applying a vibrato. The change of fret occurs every 4 beats at 60[bpm].

Sensors are able to detect the two notes in a bar but the measured capacitance follows a different pattern: in the first note (without vibrato) the measured capacitance is constant whereas in the second note (when vibrato is applyed) an oscillation of the capacitance is detected. For instance, Figure 11 shows an oscillation for the last two beats, then, the presence of vibrato is detected.

Unfortunately, vibrato depth and vibrato rate are difficult to detect because of the sampling rate of the sensing system. Although 35[Hz] should be enough to compute these parameters, it is only two or three times over the Nyquist frequency for a vibrato rate of 5 or 6[Hz]. Higher sampling rate would be appreciated.

5. CONCLUSIONS

From the results achieved in the experiments described in the previous sections, we may conclude that capacitive sensors mounted on the fretboard of a guitar are useful to the acquisition of left hand gestures. We have analyzed their capabilities in different situations, from macro to micro scale of gestures, and we have reported the limitations of the current prototype. Summarizing, the main advantages of using this technology are: (1) non intrusiveness, (2) low cost, (3) high dynamic range, (4) low background noise, and (5) high fidelity to the finger and hand movements. The cons are: (1) crosstalk, (2) slightly low sampling rate, and (3) no discrimination between strings.

As mentioned in Section 1, the study here presented focuses on the basic gestures used when playing guitar melodies. This is part of a more ambitious project in which we want to explain particular articulations used by different players, styles or musical genres. To achieve tis goal, we plan to conduct experiments with multiple guitar performers to study (1) the robustness of the prototype, (2) the gesture differences among guitarists, and (3) the gesture differences among musical styles. We are also working on hardware modifications to fix problems with sampling rate, increasing it and making it constant. Moreover, we plan to analyze the use of this sensor system on polyphonic audio, that is, playing chords, multiple voices, or melodies with harmonic/rhythmic accompaniment.

Finally, although is not the main focus of our research, we are interested in exploring the possibilities of the system as a music controller, i.e. to be used for artistic purposes.

6. ACKNOWLEDGMENTS

This work was partially funded by NEXT-CBR (TIN2009-13692-C03-01), IL4LTS (CSIC-200450E557) and by the Generalitat de Catalunya under the grant 2009-SGR-1434.

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