A Tangible Virtual Vibrating String

A Physically Motivated Virtual Musical Instrument Interface

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ABSTRACT

We introduce physically motivated interfaces for playing virtual musical instruments, and we suggest that they lie somewhere in between commonplace interfaces and haptic interfaces in terms of their complexity. Next, we review guitar-like interfaces, and we design an interface to a virtual string. The excitation signal and pitch are sensed separately using two independent string segments. These parameters control a two-axis digital waveguide virtual string, which models vibrations in the horizontal and vertical transverse axes as well as the coupling between them. Finally, we consider the advantages of using a multi-axis pickup for measuring the excitation signal.

Keywords

physically motivated, physical, models, modeling, vibrating string, guitar, pitch detection, interface, excitation, coupled strings, haptic

1. INTRODUCTION

1.1 Physical Models

Virtual models of acoustic musical instruments have been available to the music community for decades [7] [18] [13]. The models are useful for studying the physical behavior of acoustic musical instruments, and they can also synthesize sound output. Given an appropriate interface, many of the models can be played in real-time by performers.

1.1.1 Commonplace Interfaces

Often it is most convenient and simplest to control a physical model with a commonplace interface, such as a computer keyboard, musical keyboard, or mouse. This approach is most palatable if the interface matches the physical model. For instance, playing a virtual piano with a musical keyboard interface is physically intuitive, so it is easy for a pianist to transfer real-life skills to the virtual domain. However, many performers play traditional acoustic instruments lacking commonplace interface counterparts, so skill transfer to the virtual domain is not as immediate [17].

1.1.2 Haptic Interfaces

Haptic interfaces lie at the opposite end of the complexity spectrum. They apply force feedback to the performer, so that he or she feels and interacts with the vibrations of the virtual instrument as if the virtual instrument were real. In this sense, haptic interfaces can be seen as the ideal interface for interacting with virtual instruments. For instance, a carefully designed haptic bowed-string should promote better skill transfer to the virtual domain because it exerts forces on the instrument interface causing it to behave as if it were a real bow bowing a string.

When Luciani et al. implemented their haptic bowed string, they found that users strongly preferred that haptic feedback be rendered at the audio rate of 44kHz rather than at the usual 3kHz. Users made comments regarding the "strong presence of the string in the hand," "the string in the fingers," and "the string is really here" [16]. Related kinds of instruments, such as actively controlled acoustic musical instruments are essentially the same as haptic musical instruments except that the whole acoustical medium becomes the interface [6]. Haptic technologies are becoming increasingly available to the music community, but they are currently still complex enough that it is worth considering alternatives.

1.1.3 Physically Motivated Interfaces

In this paper, we investigate the middle ground in between commonplace interfaces and haptic interfaces for controlling physical models. We term such interfaces *physically motivated interfaces.* Rather than applying haptic feedback, we attempt to otherwise preserve the physical interaction between the performer and the virtual instrument as much as possible. Such interfaces are similar to Wanderley's categorization of instrument-like controllers with one important exception [17]: we state that the input quantities should be sensed so accurately that an audio-rate feedback loop could be closed around the sensor if the interface were equipped with an actuator. It follows that ideally all quantities applied to the physical model should:

- correspond to the correct quantity for controlling the physical model (e.g. displacement, velocity, acceleration, etc.)
- be linear and low-noise
- be delayed and filtered as little as possible

- be sampled at the audio sampling rate

These requirements were difficult to meet in the past due to limitations in computational power, A/D conversion, and sensing; however, today we may achieve or approximate them as we see fit. To succeed in our endeavor, we need to carefully apply knowledge from acoustics, mechanical engineering, and electrical engineering to the field of human computer interaction. In the following, we develop a physically motivated interface for a virtual vibrating guitar string.

2. PRIOR GUITAR-LIKE INTERFACES

A number of musical instrument interfaces suggest the metaphor of a guitar. While they have followed different design goals, we should at least consider how they estimate the desired pitch. For instance, the virtual air guitar uses the distance between the hands to control the pitch. Different versions of the virtual air guitar make use of magnetic motion capture, camera tracking, and acoustic delay estimation systems for this measurement [12].

The makers of the GXtar prefer to place an force-sensing resistor strip placed beneath a real string to measure both the position and pressure [14]. The Ztar [2] and the Yamaha EZ-GE [4] detect pitch with a matrix of sensors in the neck. One sensing element is used for each fret and string. The SynthAxe sports normal strings placed above matrix-type sensors [5]. The SynthAxe has additional sensors to detect string bending. A current flows down the each string, and small electric coils placed near the string measure the lateral string displacement.

Roland provides a six-channel electromagnetic pickup for electric guitar and accompanying DSP [3]. In the MIDI mode of operation, a DSP estimates when new notes are played, with what velocity, and with what pitch.[1] One drawback of this approach in general is that most detectors have noticeable delay for lower pitches because they wait at least one period. It is also difficult to construct a perfectly reliable pitch detector of this type. Consequently, performers must learn to play carefully to avoid confusing the pitch detector.

3. TANGIBLE GUITAR STRING

3.1 Separate Excitation Sensing and Pitch Detection

To ensure that the interface is physically motivated, we follow the guidelines outlined in Section 1.1.3. We sense the relevant portions of performer's gestures with as much precision as possible to preserve the guitar-like physical interaction between the performer and the virtual instrument. We would also like to preserve the physical presence of a string. To these ends, an independent string segment associated with each hand separates the problems of estimating the desired pitch and measuring the plucking excitation signal [5].

[1]In another mode of operation, the Roland system synthesizes audio more directly from the sensed signals using "Composite Object Sound Modeling". Here the pitch detector is not needed explicitly, so tracking is much improved. Since the model is not entirely virtual and its details are trade secret, we do not consider it further here.

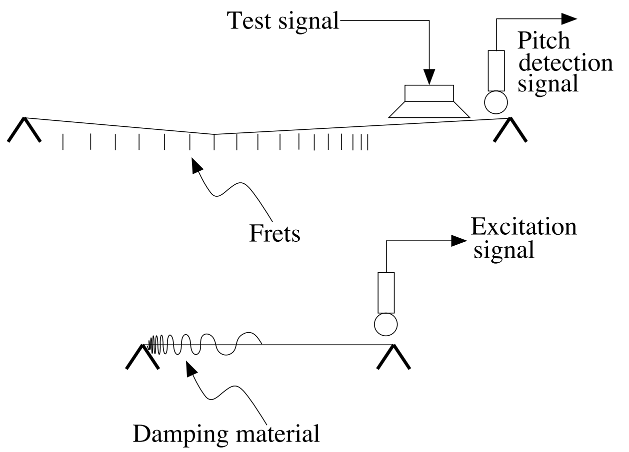

Figure 2: Two string segment approach

3.2 Signal Flow

The upper half of Figure 1 shows the signal flow for the pitch string segment; the purely acoustic components and paths are drawn in dashed lines. We detect the desired pitch of the string acoustically to help avoid incorrectly capturing higher-order effects such as string bending, slightly misplaced frets, etc. We actuate the string and measure its response. Since we know how the string is being actuated, we should be able to more accurately estimate the length of time it takes for a pulse to leave the actuator, reflect off of a fret, and arrive back at the sensor (see Figure 2, top).

Any picking, plucking, scraping, or bowing excitation is sensed via the excitation string segment and fed directly to the virtual string.[2] The lower half of Figure 1 shows the signal flow for the excitation string segment. One end of the excitation string segment should be damped passively to prevent physical resonances from interfering with resonances in the virtual model (see the damping material in Figure 2, bottom).

3.3 Two-Axis Digital Waveguide Virtual String

We model the virtual string using a simple two-axis model that takes into account the vertical and horizontal transverse modes of vibration. The ith axis is modeled using a delay line of length N_i samples and lowpass filter $LPF\ i$, which is a 3-tap linear-phase FIR filter causing the higher partials to decay faster (see Figure 3). This portion is the basic digital waveguide model used for elementary teaching purposes at CCRMA. For additional realism, the excitation signals can be comb filtered with the notch frequencies chosen as a function of the excitation's distance from the bridge [18].

While the nut is assumed to be rigid, the bridge is in general not quite rigid, hence it couples the axes together at this point. The coupling implemented in Figure 3 is actually more appropriate for modeling the coupling of the vertical axes of two neighboring piano strings, but it still results

[2]There are surprisingly few examples in the literature where some filtered form of an excitation signal measured at the audio sampling rate appears at the output. One example is the digital flute, which allows the excitation signal as measured by a microphone to be mixed with the sound synthesis output; however, in contrast with the current work, sound was not synthesized with a physical model [19].

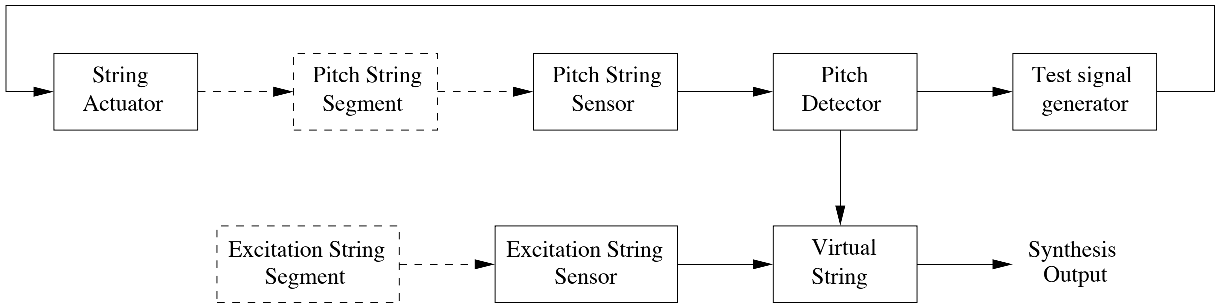

Figure 1: Tangible virtual string signal flow diagram

in qualitatively correct behavior. For instance, by choosing $N_1 \approx N_2$ such that $N_1 \neq N_2$ and $g \approx 0.1$, one obtains behavior where the energy slowly rotates back and forth between the axes of vibration [18] [15].

3.4 Prototype

A prototype of the tangible guitar string interface is shown in Figure 5. For convenience given the default hardware on a Fender Stratocaster, the two string segments are spaced horizontally instead of vertically in relation to one another. In a six-stringed embodiment, each pair of string segments would instead be placed axially-aligned with each other. In the prototype, each string's vibration is sensed using a Graphtech saddle piezoelectric pickup, as shown in Figure 4 [1].

Figure 4: Graphtech piezoelectric pickup

The magnetic actuator can be obtained by ordering the Sustainiac [11]. It conveniently replaces any one of the pickups; however, other kinds of actuators can be used instead. To prevent the actuator from affecting the excitation string segment, we choose the excitation string segment to be a regular, non-ferrous solid electrical wire. The excitation string is passively damped using felt, wrapped in such a manner to approximate gradually increasing the string's wave impedance to infinity, eliminating reflections as much as possible. In other words, the strip of felt is wrapped more and more tightly approaching the nut (see Figure 5). In some cases, it is better to damp the string less effectively. The resulting less damped reflections from the felt material cause a comb-filtering effect, which changes the timbre of the instrument as a function of excitation position as with a normal vibrating string. Note that this desirable attribute comes for free since the interface is physically motivated—the comb filter can be implemented either mechanically on the interface or virtually in the instrument model.

3.4.1 Multi-Axis Pickups

To most accurately excite the physical model, we should ideally measure the excitation in both the horizontal and

Figure 5: Tangible Guitar String Interface

vertical transverse axes of the string. This can be done using optical [10], electromagnetic, or piezoelectric sensors [8]. We have verified informally that the tangible virtual string sounds more realistic given the two-dimensional excitation.

4. WEBSITE

We have authored a website providing sound examples of the instrument in a few different configurations.[3] For example, the website includes comparisons of model output given randomly synthesized excitations, single axis measured excitations, and two-axis measured excitations. It also includes

[3] http://ccrma.stanford.edu/~eberdahl/Projects/TS

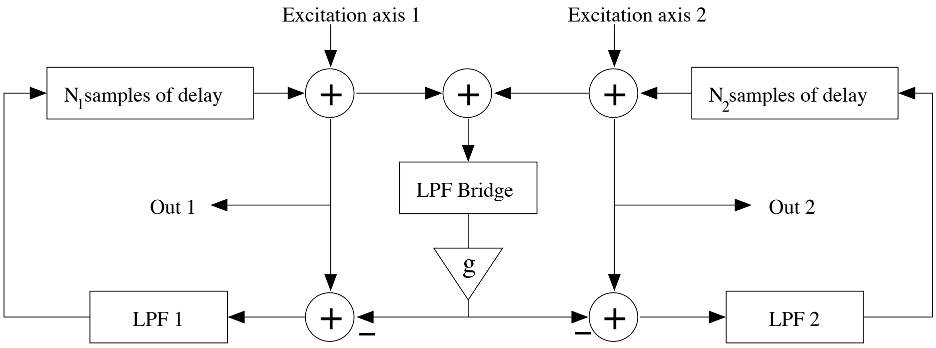

Figure 3: Two axis digital waveguide string model

model output given various excitation sources such as plucking, picking, bowing, and scraping. To enable others to excite their physical models with quality excitation signals, we provide the corresponding non-resonant excitation signals themselves. Finally, an example melody played on the tangible virtual string demonstrates the viability of physically motivated instrument design.

5. FUTURE WORK

The behavior of the interface could be further refined with force-feedback. For example, the excitation string segment could be made into a haptic device by adding an actuator. Then the piece of physical string could be joined to a portion of the waveguide using teleoperator techniques [9]. It would be essential that the string segment would have as little mass as possible to avoid loading down the virtual waveguide at the point of connection.We would also like to eventually construct a six-string version to promote the maximum transfer of guitarists' skills from real guitars to virtual guitars.

6. CONCLUSION

We have presented a physically motivated interface for controlling a virtual digital waveguide string. The excitation and pitch are sensed separately using two independent string segments. In contrast with prior interfaces, the excitation to the physical model is measured according to the principles of *physically motivated* interfaces. In particular, we measure the excitation signals with high quality, linear, and low noise sensors at the audio sampling rate. We hope that interfaces such as this one will continue to promote skill transfer from traditional acoustic musical instruments to the virtual domain.

7. ACKNOWLEDGMENTS

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