Using Haptic Devices to Interface Directly with Digital Waveguide-Based Musical Instruments

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Abstract

A haptic musical instrument is an electronic musical instrument that provides the musician not only with audio feedback but also with force feedback. By programming feedback controllers to emulate the laws of physics, many haptic musical instruments have been previously designed that mimic real acoustic musical instruments. The controller programs have been implemented using finite difference and (approximate) hybrid digital waveguide models. We present a novel method for constructing haptic musical instruments in which a haptic device is directly interfaced with a conventional digital waveguide model by way of a junction element, improving the quality of the musician's interaction with the virtual instrument. We introduce both the explicit digital waveguide control junction and the implicit digital waveguide control junction.

Keywords: haptic musical instrument, digital waveguide, control junction, explicit, implicit, teleoperation

1. Introduction

A *haptic musical instrument* consists of actuators that exert forces on a musician, sensors that measure the response of the musician, a program that determines what forces to exert on the musician, and a feedback controller that executes the program and interfaces with the sensors and actuators. Figure 1 illustrates how the musician is included in the feedback loop.

2. Prior Work

Many haptic musical instruments consist of a haptic device coupled to a virtual musical instrument, which is often implemented by way of a physical model. The common physical model types in the literature with applications to haptics are finite difference, finite element, and digital waveguide.

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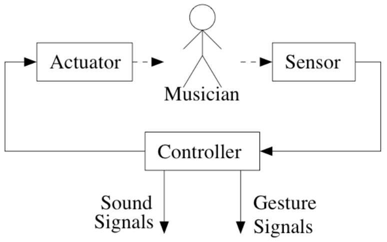

Figure 1. Musician playing a haptic musical instrument

2.1. Finite Difference Modeling

The Association pour la Création et la Recherche sur les Outils d'Expression (ACROE) currently has the longest history of model development in physical modeling for haptics. The Cordis Anima system allows virtual masses to be connected to one another by way of viscoelastic links emulating springs and dampers [1]. Jean-Loup Florens and François Poyer explain how they use nonlinear viscoelastic links to allow virtual objects to be bowed by way of a haptic device [2][3]. The differential equations describing the masses and links are discretized and solved approximately using finite difference techniques [1].

2.2. Finite Element Modeling

Finite element models have been applied in real-time for applications in haptics, but the computational requirements can be prohibitive. The computation can be reduced somewhat if the model is static [4]–i.e. if no state is required to keep track of the history of the model's motion; however, these models are not useful for designing musical instruments that exhibit resonance behavior.

2.3. Digital Waveguide Modeling

In contrast with other modeling methods, digital waveguide modeling is especially efficient because of the small number of multiply-adds and the large portions of the memory that can be factored into digital delay lines. Furthermore, when modeling most one-dimensional waveguide-based instruments, digital waveguide modeling is equivalent to discretizing the solution to the wave equation rather than approximately solving the wave equation [5]. Consequently, such digital waveguide models are more accurate than finite element and finite difference models. Finally, there is an ex-

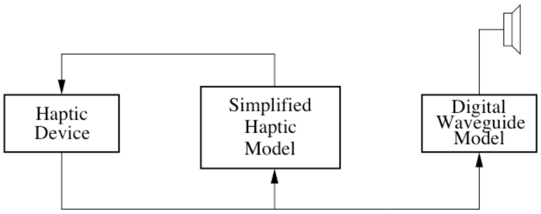

Figure 2. Signal flow diagram for hybrid modeling approach

tensive literature on calibrating digital waveguide models so that they sound like real musical instruments [5].

However, despite the advantages of digital waveguides, their application in haptics has been quite limited. Rather than directly coupling a model to a haptic device, previous research has focused on more complicated hybrid digital waveguide models. Consider the structure shown in Figure 2. A grossly simplified haptic model, such as a nonlinear spring, is typically used to govern the dynamics of the haptic device [6]. The musician's physical interaction with the instrument is limited by the simplification. Nevertheless, sound may still be synthesized as the parameters describing the state of the haptic device are fed directly into a digital waveguide model (see Figure 2). Plucked strings[1] [7][8], a bowed string [6], and a drum [9] have been previously implemented using this approach. Kontogeorgakopoulos has studied a related problem in which he simulates interfacing digital waveguides with Cordis Anima finite element networks [10].

3. Direct Modeling Approach

To improve upon the hybrid digital waveguide modeling approach, while still retaining the advantages of digital waveguides, we propose using a control junction element to directly connect a haptic device to a digital waveguide according to the signal flow diagram shown in Figure 3. We introduce both explicit and implicit variations of the junction.

3.1. Explicit Control Junction Element

The explicit control junction element for a velocity wave model is shown inside the dotted box in Figure 4. The junction consists of a sensor and an actuator placed only one sampling interval apart along a digital waveguide with wave impedance R_0. The signal a flowing to the right along the top models the velocity wave traveling to the right, while the signal b flowing to the left along the bottom models the velocity wave traveling to the left. The velocity output $v_s[n]$ at the control point is the sum of the two traveling wave components at that point a_L and b_L. The force input $F_s[n]$ causes traveling waves to exit the junction to both the left and the right. The waves are scaled by $2R_0$ since exerting a force on the control point of a virtual string should be analogous to exerting a force on the ends of two freely terminated virtual strings in parallel, each with wave impedance R_0 [5]. This model is in fact the same one that we used in 2007 for modeling the effects of proportional-integral-derivative (PID) control of a real, physical vibrating string [11].

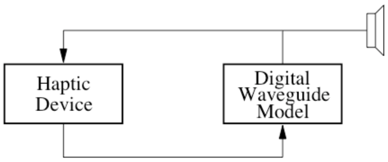

Figure 3. Signal flow diagram for direct modeling approach

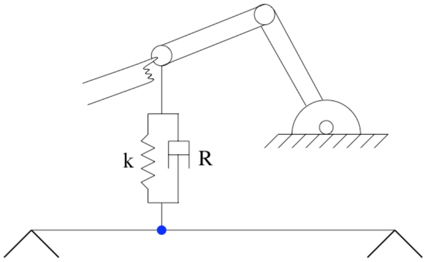

Figure 5. Teleoperator control of a virtual vibrating string

We elucidate the operation of the control junction with the help of an example vibrating string model (see Figure 4 in its entirety). The top three delay lines $z^{-S/2}$, z^{-1}, and $z^{-(N-S)/2+1}$ model velocity waves traveling to the right, and the bottom three delay lines $z^{-(N-S)/2+1}$, z^{-1}, and $z^{-S/2}$ model velocity waves traveling to the left. S/N is proportional to the distance from the left string end to the control point divided by the total string length. If f_s is the sampling rate, then f_s/N is approximately equal to the string's fundamental frequency. $H_{lp}(z)$ is a linear phase low-pass filter that causes higher string resonances to decay more quickly. $H_{lp}(z)$ also promotes stability by reducing the gain of high frequency energy reflected from the virtual string terminations.

3.2. Interfacing With The Waveguide

We can now apply standard teleoperation techniques to interface a haptic device with the control junction. It is tempting to try to bind the haptic device and virtual instrument directly together; however, this approach can be tricky because the haptic device will be able to render only a finite maximum stiffness [12]. If the instrument model were to specify a greater stiffness, then the system could become unstable. Teleoperator theory suggests instead that we should bind the haptic device and the virtual model together with a spring that limits the maximum stiffness that the haptic device needs to render. Furthermore, adding a damper as well, as shown in Figure 5, can help eliminate tendencies for the system to become unstable.

Some additional details must be considered. For instance, many haptic devices measure displacement, while the instrument model provides only a velocity output. It follows that some estimators will be required for our example. Fig-

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[1] Rob Shaw developed a haptically plucked string at Interval Research Corporation using the hybrid modeling approach, but as far as we know, he did not publish his research results.

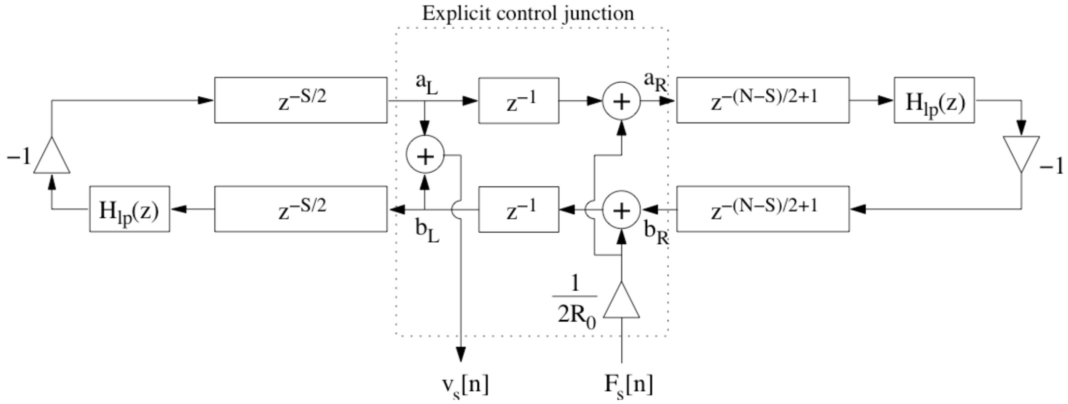

Figure 4. Explicit control junction connected to a digital waveguide model of a vibrating string

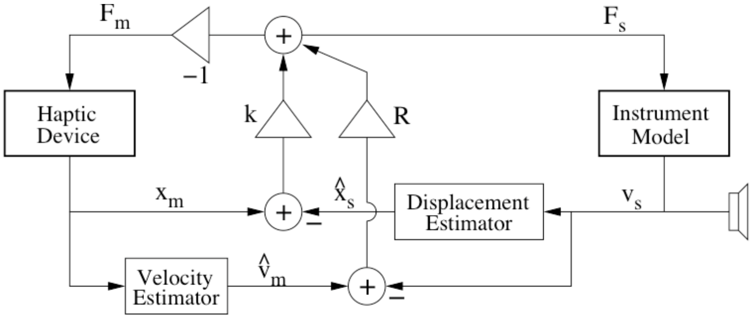

Figure 6. Signal flow diagram detailing how to implement teleoperator control

ure 6 shows how a velocity estimator can be employed to estimate the haptic device velocity $\hat{v}_m[n]$ from the haptic device displacement $x_m[n]$. Similarly, a displacement estimator estimates the displacement of the vibrating string $\hat{x}_s[n]$ from the string velocity $v_s[n]$ (see Figure 6).

The force due to the spring k and damper R is thus:

$$F_s[n] = k(x_m[n] - \hat{x}_s[n]) + R(\hat{v}_m[n] - v_s[n]) = -F_m[n]. \tag{1}$$

By allowing k and R to vary over time, we open up possibilities for simulating a wide variety of systems. To simply bind the haptic device and the virtual control point together, we use a traditional spring and damper as shown in Figure 5 [12]; to implement plucking, we neglect the damper while implementing a spring that disengages at relatively large force levels [7]; and to implement bowing, we eliminate the spring and implement a nonlinear damper [2]. Figure 7 shows the Helmholtz motion of the virtual string when bowed in the laboratory on a Phantom Model T haptic device operating at a servo/audio sampling rate rate of 19kHz.

The two single sample delay units in the explicit control junction (see inside the dotted box in Figure 4) allow instrument designers to connect arbitrary impedances to the waveguide with ease. However, the single sample delay units are non-physical and could conceivably cause some stability problems at high frequencies for large loop gains. Various other factors limit maximum loop gains such as amplifier, motor, and sensor bandwidth and nonlinearity, as well as the servo rate, etc.

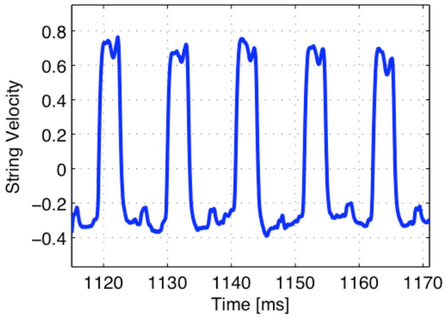

Figure 7. Helmholtz motion of haptically bowed virtual string

3.3. Implicit Control Junction Element

The single sample delay units may be removed entirely by making use of knowledge about the impedance of the load connected to the waveguide. We solve the problem for teleoperation with a spring and a damper as shown in Figure 5. If we short circuit the single sample delay units shown inside the dotted box in Figure 4, then we obtain the following:

$$v_s[n] = a_L[n] + b_R[n] + \frac{F_s[n]}{2R_0}. \tag{2}$$

To make use of substituting (2) into (1), we need to specify the displacement estimator's form, so we use a leaky integrator with pole $p \approx 1$ but $p < 1$:

$$\hat{x}_s[n] = p\hat{x}_s[n-1] + \frac{1}{f_s} v_s[n], \tag{3}$$

and we solve to arrive at the implicit control junction element's analog to (1):

$$\begin{aligned} F_s[n] = \tfrac{2R_0}{2R_0+R+k/f_s} \Big(& k(x_m[n] - p\hat{x}_s[n-1]) \\ & + R\hat{v}_m[n] - (R + k/f_s)(a_L[n] + b_R[n]) \Big). \end{aligned} \tag{4}$$

Since R and k can be changed in real-time, we can use the same strategies for implementing binding and plucking as in Section 3.2. However, (4) must be re-derived in the case of bowing to take the nonlinearity of the damper R into account. In a practical context, the solution results in calculating a nonlinear lookup "bowing table" to describe the effect of the nonlinear damper [5].

4. Final Words

Digital waveguides may be used advantageously when designing haptic musical instruments due to their accuracy, efficiency, and ease of calibration. While we have shown one example implementation, many more haptic musical instruments can be derived along similar lines by interfacing haptic devices with one-dimensional or even multi-dimensional waveguide models. The explicit control junction is more straight-forward to implement than the implicit control junction; however, the implicit control junction is slightly more accurate due to the absence of the non-physical delays z^{-1} (see Figure 4).

Both the explicit and implicit control junctions conform to what we call the direct approach (as opposed to the hybrid approach), allowing the digital waveguide model to not only serve as a sound synthesis model but also to serve as a haptic interaction model, allowing the musician to interact more intimately with the instrument. For example, Figure 8 shows the result of a musician haptically plucking a digital waveguide string (at 40ms) and then damping it (at 800ms). The string is modeled explicitly as explained in Section 3.2. The musician's finger itself provides the damping, so as the musician changes his or her grip of the haptic device, the quality of the damping will be modified. Furthermore, especially at low fundamental frequencies such as at 50Hz, the string's displacement is large enough to interact significantly nonlinearly with the musician's finger during the damping process, resulting in a buzzing sound. To listen to sound examples, see the project website:

http://ccrma.stanford.edu/~eberdahl/Projects/HDWG

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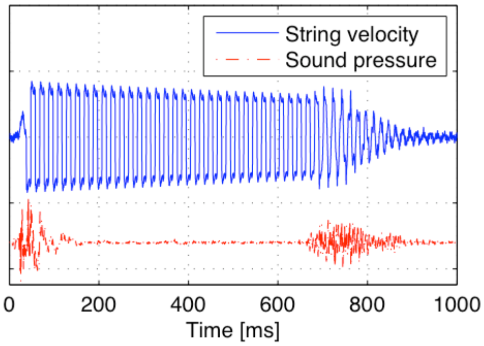

Figure 8. Plucking and damping using the direct approach

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