Bowing a vibration-enhanced force feedback device

Marcello Giordano
Input Devices and Music Interaction Laboratory,
CIRMMT, McGill University.
marcello.giordano@mail.mcgill.ca

Stephen Sinclair
Input Devices and Music Interaction Laboratory,
CIRMMT, McGill University.
sinclair@music.mcgill.ca

Marcelo M. Wanderley
Input Devices and Music Interaction Laboratory,
CIRMMT, McGill University.
marcelo.wanderley@mcgill.ca

ABSTRACT

Force-feedback devices can provide haptic feedback during interaction with physical models for sound synthesis. However, low-end devices may not always provide high-fidelity display of the acoustic characteristics of the model. This article describes an enhanced handle for the Phantom Omni containing a vibration actuator intended to display the high-frequency portion of the synthesized forces. Measurements are provided to show that this approach achieves a more faithful representation of the acoustic signal, overcoming limitations in the device control and dynamics.

Keywords

Haptics, force feedback, bowing, audio, interaction

1. INTRODUCTION

Impedance haptic devices, also commonly referred to as force feedback devices, are a unique class of controllers which read position information and respond with force output, in a continuous and mutually influencing energy exchange. These systems have been extensively used in recent years in human-computer interaction. Applications vary from the design of medical and surgical devices to teleoperation and virtual reality. In this paper we will focus on the application of these devices for the simulation of bowing interaction.

Force feedback devices vary widely in performance characteristics, such as force capability, inertia, friction, materials used, and degrees of freedom, which all influence the capability for faithful display of forces [7]. These factors typically affect device cost: most high-performance systems have prices at least 10 times higher than low-end device.

There is also some variety in how these devices communicate with a computer, which affects control capabilities. While some research devices such as the Ergon-X system from ERGOS Technologies (ACROE, INPG) utilize a dedicated controller for interaction at high frequencies [5], many commercial devices make use of standard peripheral buses such as USB or Firewire (IEEE1394), and depend on the computer's general-purpose operating system for control, which is subject to unpredictable I/O pauses. This implies an asynchronous divide between audio and haptic computations, in particular enforcing the use of different sample rates for the two channels.

NIME'12, May 21 – 23, 2012, University of Michigan, Ann Arbor.

A result of poor communication speed and low-cost materials is that high-quality acoustic interaction is difficult to achieve on low-end devices. Here we present an enhancement of the SensAble Phantom Omni, a common low-end device found in research institutes, which embeds a vibrating actuator in the device's handle. Our intent is to increase the effective bandwidth of the acoustic display, while preserving the capacity for force effects such as friction.

Since there are many factors to consider in comparing different haptic devices [7], we do not attempt in this paper to compare the resulting system with existing high-fidelity devices. Instead, we will characterize by comparing the possibilities of the Omni with and without vibrotactile enhancement, and discuss measurements during acoustic simulation.

1.1 Vibrotactile Feedback

The role of vibrotactile feedback in musical interaction has been extensively explored in the literature. Many authors, starting with Chafe [4], have investigated which tactile cues are used by musicians to retrieve information about their interaction with an instrument. Others, like [3], have explored the possibilities given by vibrating actuators to enhance the capabilities of controllers and digital musical instruments (DMIs) in providing the user with information about his/her actions.

In this paper we make use of vibrating actuators to enhance the vibration capability already present in the haptic device. Given the importance of tactile cues for a proficient interaction with the instrument, extending the frequency range could provide the player with useful information about the behaviour of the bowing model.

1.2 Bowed string force interaction

Several works have investigated using a haptic device for bowed string interaction. As mentioned, Florens [5] used the Ergon-X system to implement a modal synthesis model based on mass-spring interaction. Berdahl et al. [2] connected a haptic device with a digital waveguide string model. We proposed the DISTPLUCK model avoiding some issues with noise in the velocity signal [12]. We chose to work with DISTPLUCK since it is robust to sampling issues, but for our purpose of synthesizing a bowed string through a vibration motor, any of these models would be adequate.

2. EXPERIMENTAL SETUP

In this section we describe our experimental setup which we used to test our bowing algorithm with the augmented Omni haptic device.

2.1 Augmented Phantom Omni

The SensAble Phantom Omni haptic device comes, in its factory configuration, with a detachable handle connected to the end effector by means of a $1/4$-inch phono connector. This allowed us to replace the existing handle with a custom-built one, embedded with an actuator: the Haptuator produced by Tactile Labs [1] (Fig. 1). This actuator provides independent control of frequency and amplitude of the vibration, a quality not normally found in common solutions such as tactors or rotating motors—it acts much like a loudspeaker, and is linear within its operating range [13]. It is driven by an amplified mono audio signal and provides a rated bandwidth from 50 Hz to at least 500 Hz [1].

To build our tactile-augmented handle we fixed the actuator inside a plastic pipe of the same diameter as the original handle. A female phono connector, also embedded in the pipe, provided a good connection to the haptic arm.

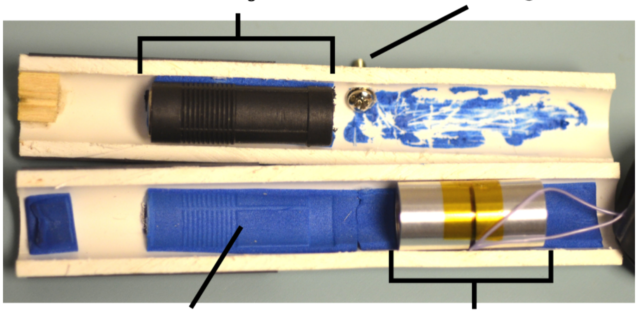

Figure 1: Interior of modified handle, showing Haptuator (right) and the phono connector (left).

2.2 Equipment and testing procedure

We used a laptop to control both the haptic device and the actuator, and to record the data. A professional Bryston 4B SST power amplifier was used to drive the actuator. The recordings have been performed using an ADXL202 accelerometer (Analog Devices), tightly secured to the handle with a screw, and connected to a National Instruments USB-6009 acquisition board (see fig. 2). The accelerometer was configured using external capacitors per the datasheet for its maximum bandwidth of 2500 Hz.

We tested the device in two different conditions:

1. The vibrating handle was turned off and the bowed string algorithm drove the Omni motors with a force signal filtered to 480 Hz;
2. The handle actuator was switched on, and the algorithm provided velocity-opposing low-frequency feedback through the Omni motors while stimulating the handle with the high-frequency portion of the same force signal. (See sec. 4.1.)

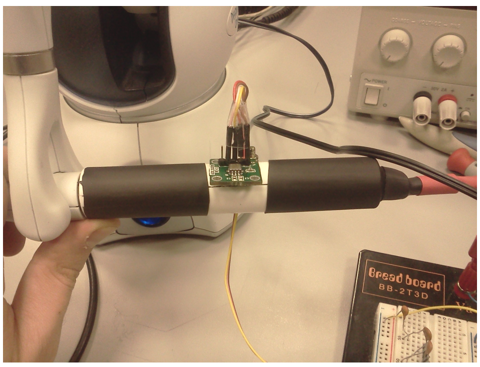

Figure 2: The Sensable Phantom Omni with the vibrotactile augmented handle.

In this way we hoped to compensate for the resonant characteristics of the device's kinematic chain and be able to display more harmonics than with the Omni alone.

3. RESULTS

We analyzed the acceleration recordings of the device alone and augmented with the vibrating handle. The responses of two similar bowing gestures in each condition were compared for a string tuned to a fundamental of 110 Hz.

In fig. 3 we can see frequency domain plots of force and acceleration signals for motor control in two conditions. In fig. 3(a), the Haptuator was used to deliver high-frequency feedback. The control signal, delivered at 48 kHz, has large, precise peaks for every harmonic of the 110 Hz string. It can be seen that this is well-reproduced in the acceleration.

In comparison, the Omni-only condition, fig. 3(b), required low-pass filtering to be delivered over the 1000 Hz digital channel, and this restricted the demanded harmonics. Moreover, the acceleration does not reproduce all demanded frequencies, as can be seen by the missing peaks at 110 Hz and 330 Hz. There is one distinct peak at 220 Hz, and one at 440 Hz, but the string fundamental is missing, likely due to anti-resonances in the device dynamics.

4. DISCUSSION

In this section we discuss some technical issues related to control of the dual-channel haptic device composed of the Omni and the augmented handle. We describe our approach, which consisted of filtering the force command into two separate bands.

As we will see in section 4.1, this imposed some delay due to filtering, and due to transmission between I/O devices, and we therefore include a brief discussion of this topic. Frequency analysis of the recordings (fig. 3) seems to confirm that low-pass filtering the force command was an adequate approach, and our impressions were that any problems introduced by delay seemed to be qualitatively masked by the Haptuator action.

Similarly, there were no noticeable problems caused by the delay in the audio path, that we estimated to be approximately 22 ms.[1] This may be explained by noticing that high-frequency feedback may often be considered an open-loop phenomenon, since our muscles cannot, at least voluntarily, react with such high speed to velocity-opposing forces—at most, some non-linear interaction with the skin may be affected. This is different from position-feedback effects such as the *virtual wall*, where very high-speed switching between impedances is required in order to simulate a stiff non-linearity.

4.1 Dual-channel force feedback

Several previous projects have used redundant actuators in series to control a single axis of force feedback. For instance, Morrell [10] used two elastic-coupled motors in series to actuate a single joint. A large motor provided large, sustained forces while a smaller motor was responsible for delivering fast response. Millet [9] used a similar viscous-coupled two-motor design in a haptic device to good effect.

[1] Measured time between transient accelerometer reaction to Omni motors and the Haptuator control voltage in a non-filtered condition. The audio buffer size, 512 samples at 48 kHz, accounts for ∼11 ms, which could be improved. It is doubled by buffered transmission from Omni thread. This measure neglects closed-loop feedback delay of 1 ms.

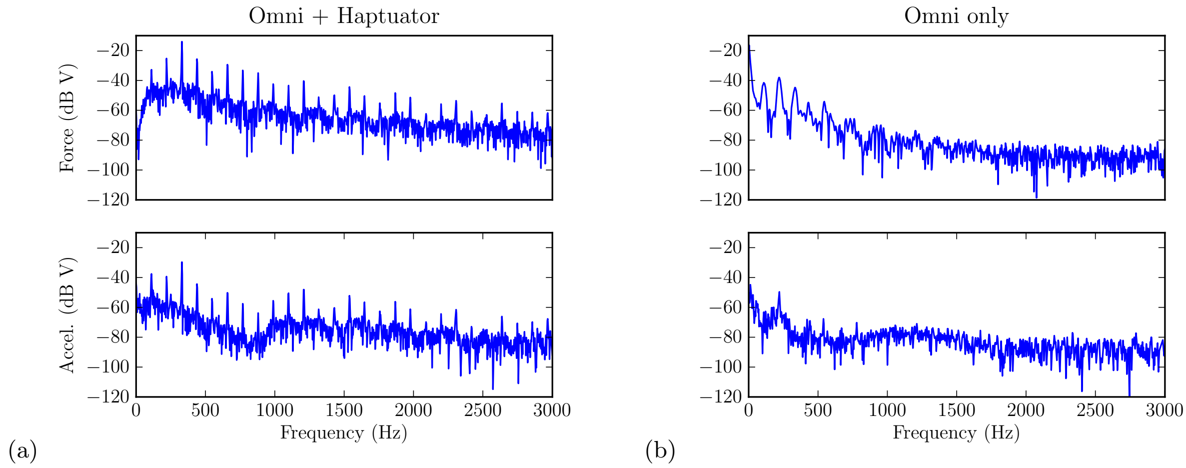

Figure 3: (a) Frequency response of the Haptuator-enhanced Phantom Omni running DISTPLUCK. Force command voltage for Haptuator (top) is passed through a 100 Hz high-pass filter; force to Omni motors through a 100 Hz low-pass filter. (b) Frequency response of the Phantom Omni without Haptuator enabled. Force signal to Omni (top) is passed through a 480 Hz low-pass filter to match maximum sample rate of digital control.

In our case, several Omni motors act on the same Cartesian axis, and rather than using two motors at each joint, we propose adding a single vibration actuator directly at the handle. A similar approach has been applied to texture interaction, using a voice-coil for vibration actuation [8]. The only similar musical example we are aware of is the PHASE project [11], but no details are given of its use.

For this configuration, due to the differing frequency characteristics of the actuators as well as the restrictions imposed on the respective control signal bandwidths, the division of labour between the two actuators can effectively be thought of as a straight-forward two-band filter. Despite inter-channel delay, we wish to calculate audio and haptic feedback *as if* they were synchronous channels, since they result from the same physical model. The audio (and vibration force) is then transmitted to the sound system asynchronously, necessitated by the computer architecture.

The bowed string model is calculated at the audio rate of 48 kHz. Since the Omni is only controllable via a 1000 Hz digital signal over a Firewire connection, in a normal configuration it is necessary to pre-filter the signal to avoid fold-over aliasing. As mentioned, we used a 480 Hz 2^{nd}-order Butterworth filter for this purpose.

The sound system is used to output a stereo signal consisting of sound—the string velocity at a point on the waveguide—in one channel, and the Haptuator force command in the other. Due to the nature of the Haptuator as well as the AC-coupled audio electronics, it is necessary to high-pass filter this signal. However, we can simultaneously control the Omni motors using the low-frequency portion of the signal. This dual-band complementary configuration acts to additively combine the desired force signal at the handle.[2]

The exact frequency division can be adjusted to match the capabilities of the actuators: the Omni motors can be controlled at 1000 Hz, ostensibly generating vibrations up to 500 Hz, but in practice they have difficulty with certain frequencies due to the kinematic configuration and nature of the plastic materials used. In particular we have noticed an anti-resonance at about 100 Hz, which is close to the tuning of our string. Chirp analysis on 3 axes using the Omni motors confirmed the presence of notches at approximately 20, 37–50, and 90–120 Hz locations, varying somewhat with axis and stimulus amplitude. On the other hand they provide a net resistance to motion that is not possible with a vibration motor. By placing the frequency division just before 100 Hz, significant energy was achieved in this region and well above 500 Hz from the Haptuator, making up losses due to dynamics and control.

[2]This additive property suggests that care is needed to avoid phase cancelation, which we do not address here.

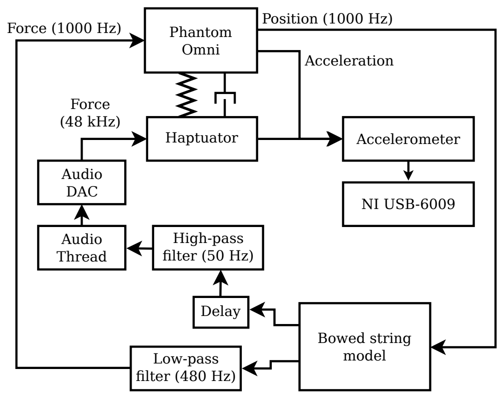

Figure 4: System diagram, where position of one horizontal axis implements a bowed string model. Vertical axis is not shown, but controls "bow pressure" in the bowed string model.

4.2 Handling delay in the output path

It can be seen in fig. 4 that there are several sources of delay in the proposed system: firstly, the string model is calculated in the haptic loop, and audio data is sent to the sound card via a decoupled audio thread. This is necessary because a single synchronous model is used to control both outputs, but the computer provides separate clocks for each output device. Additionally, the audio system requires data in chunks of a millisecond or more. Since the Firewire bus and thread scheduling cannot guarantee hard timing, it is also necessary to compensate for any jitter. Thus, a buffer is required to match these differing timing requirements.

Although we wish to treat the two outputs as synchronous, in reality they are not, since they do not share a clock. Thus,

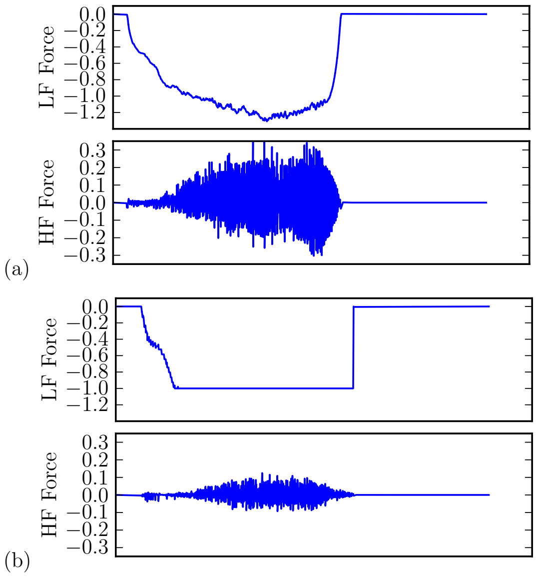

Figure 5: Similar bow strokes, moving horizontally while pressing down, and then lifting the bow. Two conditions: (a) Omni motor force low-pass filtered at 48 Hz. (b) Omni motor force controlled by position-based Dahl friction.

we have found that it is not adequate to calculate the ideal number of samples per timestep; e.g. 48 samples of audio per 1 ms haptic step. Instead, it is necessary to measure the real amount of time between I/O intervals and buffer the correct number of audio samples accordingly. The result otherwise is that the audio thread may exhaust the incoming buffered stream and temporarily generate a "glitch." We presume that this is due to drift between the timing of the device I/O and the sound system's internal clock. Good results were achieved using the `gettimeofday` function on Linux, and `QueryPerformanceCounter` on Windows.

Secondly, the low-pass filter in the Omni force feedback path also may contribute some delay, making the force response feel soft and imprecise. Since the filter's job is solely to reduce the output to a smooth, non-vibrating response in the Omni motors, one approach is to use a different rendering algorithm for the low-frequency path. An independent smooth friction model such as position-based Dahl friction [6] may be executed, and will superpose with the bowed string model without problems. This technique is demonstrated in fig. 5, where we can see that Dahl friction provides a much faster on-set and release, with a clean velocity-opposing net force during the stroke.

5. CONCLUSIONS AND FUTURE WORK

In this paper we presented an extension of a commercially available, low-end haptic device, the SensAble Phantom Omni, to replace the device's handle with a tactile-augmented one. The new handle is embedded with a vibrating actuator that can be controlled by an amplified audio signal. We used this augmented device in conjunction with a model for simulating bowed string interaction, so that the added vibration could compensate the device dynamics and control.

Using acceleration recordings, we show that with this approach the range of frequencies displayed is increased. Although we have not rigorously shown it here, we believe that this increases the perceived quality of the interaction—a position born out in studies on texture display [8].

We did not attempt to precisely match the acceleration profile of the device with real-world interaction, as suggested in [8]. This may further improve the realism achievable by these means, although we find the simple dual-band control strategy applied here quite satisfying. Nonetheless, with more precise control and future studies with musicians, we hope to show that this approach may improve realism in acoustic interaction using low-end haptic devices.

6. ACKNOWLEDGMENTS

We would like to thank the Natural Sciences and Engineering Research Council of Canada for the NSERC Discovery Grant partly funding this research, as well as the staff at CIRMMT for their expertise with the high-quality audio amplifier equipment used to drive the vibration motor.

7. REFERENCES

[1] TL002-14-A (Haptuator) data sheet, 2011. Available: `http://www.tactilelabs.com`.

[2] E. Berdahl, G. Niemeyer, and J. Smith, III. Using haptic devices to interface directly with digital waveguide-based musical instruments. In *Proc. NIME*, pages 183–186, Pittsburgh, PA, 2009.

[3] D. Birnbaum and M. Wanderley. A systematic approach to musical vibrotactile feedback. In *Proc. ICMC*. ICMA, 2007.

[4] C. Chafe. Tactile audio feedback. In *Proc. ICMC*, pages 76–79. ICMA, 1993.

[5] J. Florens, A. Luciani, C. Cadoz, and N. Castagné. ERGOS: Multi-degrees of freedom and versatile force-feedback panoply. In *Proc. Eurohaptics*, pages 356–360, 2004.

[6] V. Hayward and B. Armstrong. A new computational model of friction applied to haptic rendering. In *Proc. of Int. Symp. on Experimental Robotics*, pages 403–412, London, UK, March 2000. Springer Verlag.

[7] V. Hayward and O. R. Astley. Performance measures for haptic interfaces. In G. Giralt and G. Hirzinger, editors, *Robotics Research: The 7^{th} Int. Symp.*, pages 195–207, Berlin, Germany, 1996. Springer Verlag.

[8] W. McMahan, J. Romano, A. Abdul Rahuman, and K. Kuchenbecker. High frequency acceleration feedback significantly increases the realism of haptically rendered textured surfaces. In *Haptics Symp.*, pages 141–148. IEEE, 2010.

[9] G. Millet, S. Haliyo, S. Régnier, and V. Hayward. The ultimate haptic device: First step. In *Proc. Eurohaptics Conf. and Symp. Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 273–278, 2009.

[10] J. Morrell and J. Salisbury Jr. In pursuit of dynamic range: Using parallel coupled actuators to overcome hardware limitations. In *Int. Symp. on Experimental Robotics*, pages 263–273, 1995.

[11] X. Rodet, J. Lambert, R. Cahen, T. Gaudy, F. Guedy, F. Gosselin, and P. Mobuchon. Study of haptic and visual interaction for sound and music control in the PHASE project. In *Proc. NIME*, pages 109–114. National University of Singapore, 2005.

[12] S. Sinclair, M. Wanderley, V. Hayward, and G. Scavone. Noise-free haptic interaction with a bowed-string acoustic model. In *World Haptics Conference (WHC), 2011 IEEE*, pages 463–468. IEEE, 2011.

[13] H.-Y. Yao and V. Hayward. Design and analysis of a recoil-type vibrotactile transducer. *J. Acoustical Society of America*, 128(2):619–27, Aug. 2010.