Mark Havryliv, Greg Schiemer and Fazel Naghdy
Sonic Arts Research Network
University of Wollongong
Wollongong, 2522
Australia
mhavryliv@hotmail.com
schiemer@uow.edu.au
fazel@uow.edu.au

Haptic Carillon: Sensing and Control in Musical Instruments

Abstract

This paper discusses the proposed design of a haptic-rendered practice carillon clavier. This instrument will produce a haptic feedback coupled with a responsive bell synthesis algorithm in order to replicate the authentic playing 'feel' and sound of a conventional mechanical carillon.

An original classification scheme for haptic devices is presented with two principle goals: 1. to forge a conceptual understanding of the nature of a haptically-enabled version of a traditional instrument, and 2. to identify which existing haptic projects contribute towards a technical roadmap for the haptic carillon. Devices surveyed include both musical instruments and other applications that clarify the scope of haptic principles.

A distinction is drawn between devices which utilise haptic force-feedback and devices which strongly engage a user's tactile sense. It is argued that in the latter case, an opportunity for the composer/instrument builder is lost when the relationship between an instrument's audio response is not linked to a complementary haptic response, as is the case in traditional instruments.

Introduction

Over the past three decades the way music is created, produced and distributed has radically changed. Musical instruments that incorporate computer synthesis and computer control are now a driving force in many parts of today's music industry. These instruments were designed on the premise that real-time auditory feedback between performers and the sounds made by their instruments is the sole requirement for expressive performance.

This assumption overlooks the role of tactile and kinaesthetic feedback in conventional acoustic instruments, where a performer can feel the physical reaction of the instrument to their gestures and can adapt the sound accordingly.

Most contemporary research in this field is focused in a mono-directional sense on the relationship between a performer's physical input and the audio response of an instrument. Composers are increasingly aware that a sophisticated audio synthesis algorithm requires an equally sophisticated input mechanism or controller, i.e. one whose range of physical input matches the controllable parameters of an algorithm.

Such research tends to develop models for new electronic instruments which increase the number of controllable parameters required to interact with multi-parameter synthesis algorithms (Cook 1999, 2004; Wanderley et al. 2004; Gadd 2002; Levitin et al. 2002).

Typically, these new digital instruments also aim to increase the range of 'expression' a performer may exercise in the performance of the instrument (Arfib et al. 2005).

Although the physical relationship between performer and instrument is at the core of such designs this does not mean that this relationship has been realised to its full extent. To realise the full potential for greater expressiveness and control, one must also consider the reciprocal relationships between instrument and performer where sensations produced by the instrument are transmitted to the player.

Depending on the nature of the instrument, these sensations are felt in the fingers, feet, lips and other parts of the body (Rovan et al. 2000). In most current computer musical instruments, this vital link, known technically as haptic feedback, is missing.

Force-feedback

Force-feedback is the electromechanically generated sensation of pressure used in a haptic interface. These and other techniques related to haptics have already found practical applications in areas such as robotics used in process control, detection of landmines, machine vision, mechanical assistance for the disabled and medicine (Xue et al. 2000; Shahri et al. 1998; Naghdy 1995, 2000).

In a haptic musical instrument interface force-feedback must be produced in response to a performer's gesture and it must be felt through the physical mechanism that a performer plays. While the design and functionality of haptic devices will vary according to the kind of instrument being simulated, a performer should be able to play such a device as though an actual instrument is being played.

A haptic interface must also address issues associated with control of digitally synthesised music. To do this, smart algorithms are needed to convert performance gestures into electrical signals and to simulate ways that synthesised instruments react to force feedback.

Haptic Carillon

Using a traditional carillon as a model our project will define the characteristics of a haptic interface for digitally synthesised music that can closely produce the feel of a traditional acoustic instrument.

The mechanical design of a carillon clavier permits musical expression through variations in touch. There are many similarities between the carillon and other keyboard musical instruments but in its performance technique the carillon is unique. A carillonist controls the intensity of touch through the pressure felt on the clavier keys, shown in Figure 1.

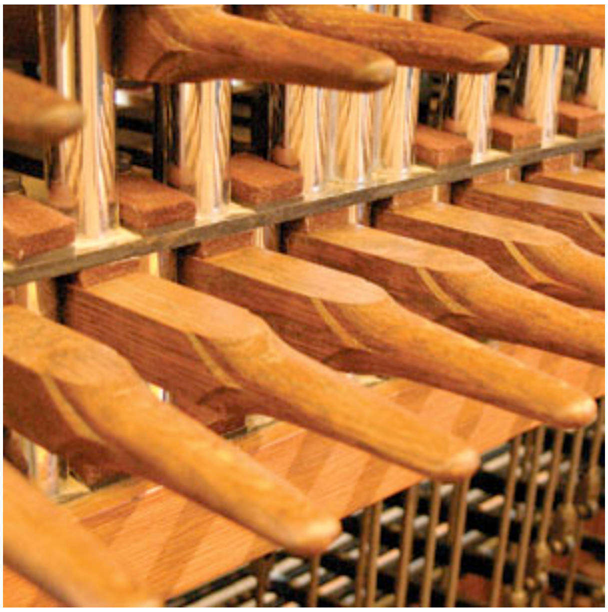

Figure 1. *The clavier keys of a carillon. Courtesy of the National Carillon, Canberra, Australia.*

Unlike the piano keyboard this pressure can be continuous as well as momentary. This makes reproduction of haptic feedback required for carillon playing applicable for performance interfaces other than keyboards. Whereas a simple electrical hammer activated by an electronic key will strike a bell with the same force every time, it cannot produce the range of expressive variation available to a performer on an actual carillon keyboard.

The carillon mechanism

Ever since mechanically actuated musical instruments were developed, the quest for more expressive music gave rise to musical instruments of great mechanical sophistication. The development of the carillon as an expressive musical instrument was made possible as bells were actuated by metallic clappers attached to a clavier keyboard instead of using ropes pulled by teams of bell ringers.

The keyboard has a hand key (baton) for each note in the carillon. As shown in Figure 2, the manual key in a carillon keyboard is linked to the bell's clapper by two wires separated by a bell crank. The transmission system in the bell chamber transfers vertical motion of the manual key to a horizontal wire that pulls the bell clapper.

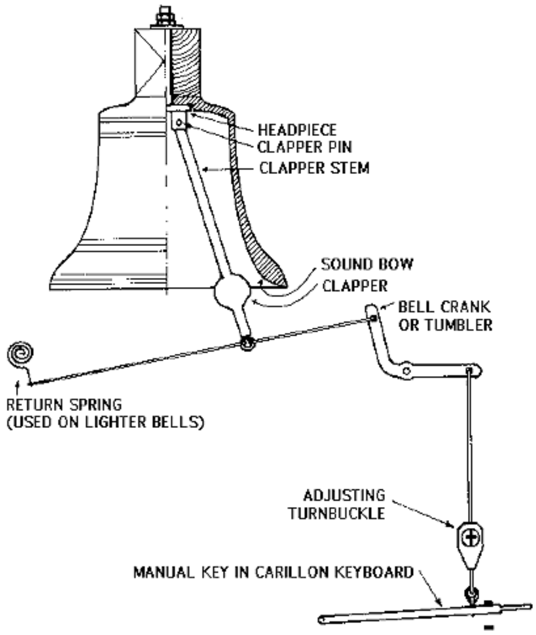

Figure 2. *The carillon mechanism.*

Haptics in New Musical Instruments

New instrument designs or methods of performance which deal specifically with the sense of touch can be categorised using the following four characterisations:

- **Active haptic (force-feedback) vs. Pseudo-haptic (tactile)** – an active haptic device provides a force-feedback response to a performer's action. An example of this is the 'Haptic Turntable' (Beamish 2004), which replicates the resistance in a real turntable using a variable-speed motor.
  By contrast, a pseudo-haptic device will imitate haptic feedback or engage a user's tactile senses. Methods of imitation include manipulating non-tactile senses or by issuing simple vibrations. 'Panphonen' (Pittarello 2001) is an example of a system which uses audio cues to manipulate a tactile space. Pseudo-haptic devices may also simply engage a performer's tactile sense in a significant way, i.e. augmented instruments or novel controllers which require significant physical input but do not otherwise issue any force-feedback. An active haptic device will output linear and/or discrete feedback.
- **Linear feedback vs. Discrete feedback** – if force-feedback exists, does its operation change during the use of the instrument? An example of discrete feedback is the 'TouchSound' interface (Chu 2002), a haptic interface for multi-track sound editing. It uses a control knob as a feedback device and the feedback is relative to the position of the sound file being edited, i.e. each 360 degree rotation will deliver different levels of feedback. The term 'discrete' is used because these types of devices commonly issue haptic 'cues' extraneous to their normal function.By contrast, the 'Fabric' interface (Huang 2003) delivers a consistent haptic and audio response, based on virtual traversal of a stationary piece of fabric. Haptic

force-feedback devices are likely to be primarily linear but occasionally use discrete cues.

- **Complex response vs. Simple response** – a complex system is one whose non-haptic output has a complex relationship with user input. A simple system may not even allow user input; many non-musical pseudo-haptic devices are simple systems. Conversely, most active haptic devices are complex systems. The ‘PHASE’ project (Cahen et al. 2005), for example, is a game-based improvisation environment in which a player navigates a virtual ball through a 3D environment using a haptic arm. The arm applies force-feedback to the player depending on the texture of the world and any obstacles the virtual ball encounters. Music is generated by analysing the player’s input and correlating that with the current state of the music and their position in the game.

  By contrast, ‘T-Rhythm’ (Miura 2005) is a much simpler system, allowing no user input whilst simple vibration output corresponds precisely to a melody displayed on a computer screen.
- **Replicate vs. Novel controller** – a replicate device is one which aims to replicate or augment an existing instrument. They generally retain the aural and physical characteristics of the existing instrument. The ‘Haptic Carillon’ aims to be one such instrument.

  A novel controller, however, seeks to create either a new physical input method or alter the function of an existing instrument to an extent where the sound production and/or input method is unlike the existing instrument. The ‘nukelele’ (Cook 2004) is an attempt at a fully virtual string instrument. It generates a synthesised string sound based on data from sensors where strings would be found on a standard guitar.

These characteristics can be implemented as a series of questions, which illuminate the differences between instruments all of which share some degree of tactile interaction. The fourth characteristic, whether a device is a replicate or not, bears less consequence in the categorisation of the nature of its tactile interaction, and is left out of the following figure.

Figure 3 demonstrates the process of interrogation which leads to this categorisation. The first question determines whether a device is pseudo-haptic or features haptic force-feedback. These characteristics are mutually exclusive, forcing a device into either the left or right side of the diagram.

If a device uses force-feedback, it is then determined whether this feedback is linear, discrete or both. At this point, the device is either a linear haptic device, discrete haptic device or pseudo-haptic device.

The next question is asked of every device and goes to whether or not the device’s non-haptic output has a complex relationship with user input. After this question is answered, 6 categories are left: the four categories on the left are all active force-feedback devices and the two on the right are pseudo-haptic.

This 4 point method of categorisation frames the diverse range of devices and research efforts that come under the guise of haptics. This is not only important when reviewing research, but in understanding what is relevant to one’s own research.

For instance, the large amount of research dealing with user (performer) perception of synchronicity between audio and haptic response is primarily interested in augmenting the relationship between a user and a computer; this often comes under the banner of ‘multimodality’, developing models for Human Computer Interaction (HCI) based on a combination of visual, aural and kinaesthetic senses.

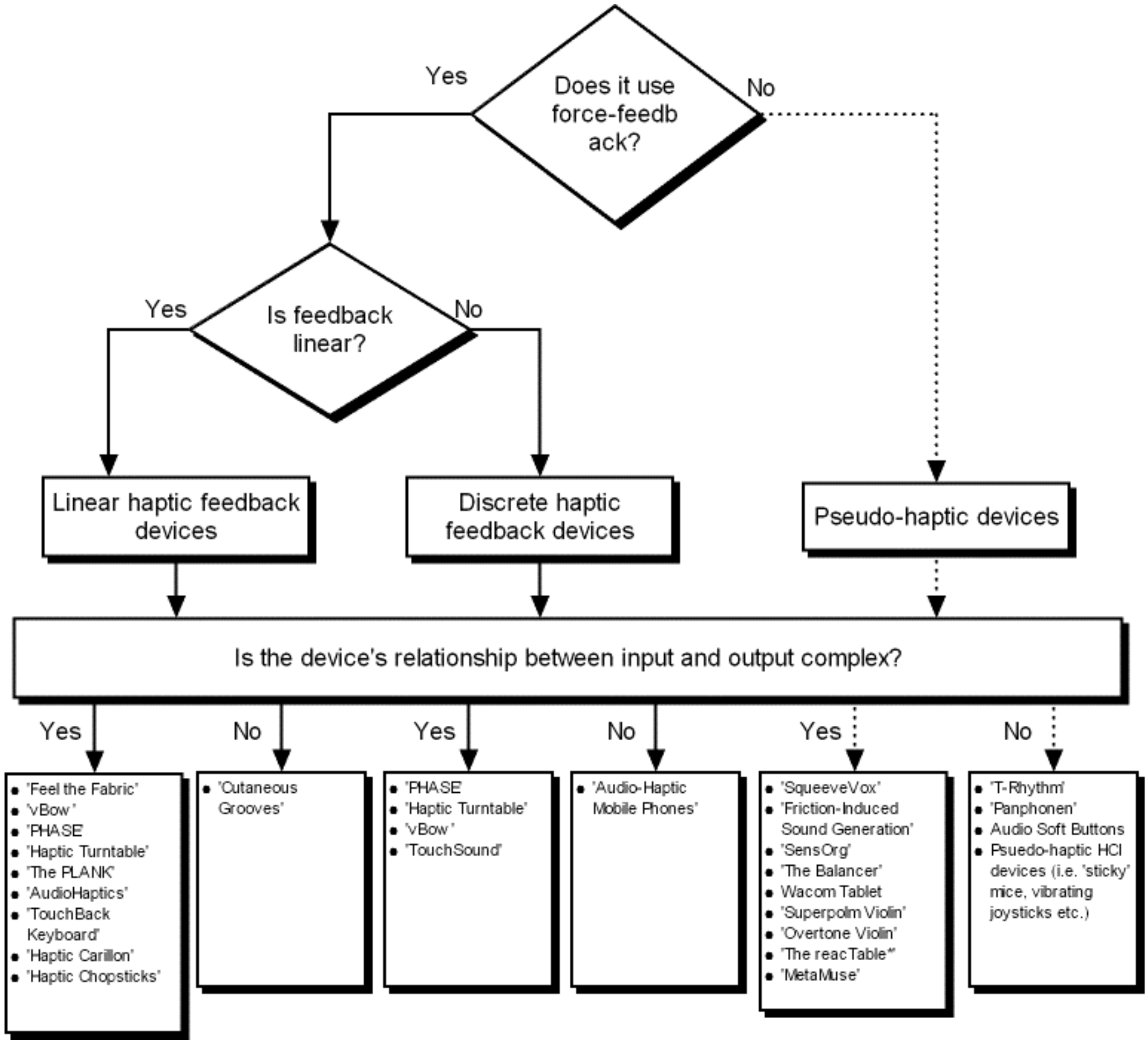

Figure 3. *A flowchart demonstrating the method by which a device may be categorised. Note that some de vices appear in more than one category, especially linear and discrete haptic feedback devices. References for the devices listed can be found in the references section of this paper.*

While this research is relevant for developing haptic feedback in order to imitate an existing instrument or set of actions, its conclusions must be considered within a context of its motivations, i.e. non-musical, experientially-driven HCI design. One is particularly struck by the importance of this distinction when observing projects which boast complex and creative haptic systems coupled with veritably simple audio systems, and vice versa. A framework for analysing the diverse range of work is necessary to extract the most relevant information from a seemingly irrelevant project.

Pseudo-haptic / Tactile

This first layer of description refers to the difference between two types of devices: one which engages a performer's tactile senses in some limited way, and a device which actively uses force-feedback in a mechanically sophisticated fashion. A haptic device will use force-feedback as a primary interface between a performer's intention and the device.

Devices which do not employ haptic force-feedback can be divided into two groups, as shown at the bottom right of Figure 3. This division is based on the complexity of a device's relationship between input and output. Two trends become clear:

- Devices either strongly engage a user's tactile senses or attempt pseudo-haptics.
  Augmented instruments and novel controllers are more likely to engage a performer's tactile senses, while non-musical devices typically employ some type of pseudo-haptics.

- Augmented instruments and novel controllers are more likely to have a complex relationship between input and output.
  By contrast, devices designed to interact with desktop computers, either to assist learning or accessibility, exhibit less complex relationships.

The relationship between the type of haptic/pseudo-haptic device and the general level of complexity in the relationship between input and output is shown in Figure 4.

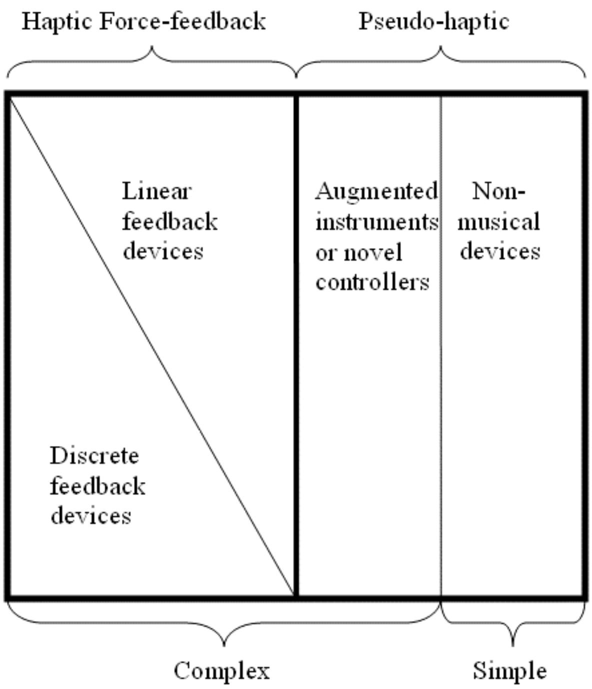

Figure 4. *A modified Ven diagram showing that linear feedback devices, discrete feedback devices and pseudo-haptic musical devices are more likely to have complex relationships between user input and system output.*

Pseudo-haptic Devices

Pseudo-haptic devices generate haptic output for a specific purpose, usually to increase the accessibility of a computing interface or for desktop computer-assisted learning. For this reason, their haptic response is relatively simple, typically limited to discrete cues which indicate the user's current relationship with the system. This is unlike a traditional acoustic instrument where the haptic response is a continual product of the physical characteristics of the instrument and a player learns to incorporate this 'feel' into their playing and control.

Pseudo-haptics for Accessibility

'Auditory Soft Buttons' (Fernström et al. 2005) is a system aimed at increasing the usability of handheld computing devices by removing the need for the screen to be visible. It helps a user navigate 'soft' buttons on a screen by creating a pseudo-haptic environment using auditory cues, or *earcons* (Blattner 1989). A user moves their finger across a touch sensitive screen; whenever their finger moves into the region of a button, a 'click' sound is produced along with a friction-like sound which indicates their finger is over a button. A click sound also indicates when their finger leaves the area of the button.

The user forms a tactile relationship with the device by cross-correlating several different sensory inputs (Johannsen 2004). This is a pseudo-haptic display which is based on the manipulation of non-tactile senses.

Pseudo-haptics for Learning Assistance

The 'T-Rhythm' device (Miura, 2005), on the other hand, is used to learn rhythm. The device consists of a small vibrating motor enclosed in a box which is held by the user whilst they observe a desktop computer. The computer displays and performs a melody and the vibration device vibrates in time with the rhythm of the melody at one of three strengths, depending on the volume of the note.

Musical Instruments

Augmented Instruments

An augmented or hyper instrument is an "[enhanced] traditional instrument with various sensors to enable features of the gestural activity of performers to control augmentations of the existing instrumental sound" (Bowers 2005). Builders of such instruments are also motivated by a realisation that several physically expressive motions remain underutilised in the performance practice of most traditional musical instruments. This typically leads to the development of instruments which require a performer to be in far greater physical contact with the instrument, or at the least have the physicality of their performance analysed in the search for gesture (da Silva et al. 2005; Scavone et al. 2005; Palacio-Quintin 2003; Burtner 2002).

The 'Overtone Violin' (Overholt 2005), for example, is an electronic violin built from scratch which adds buttons, rotary, linear and spring-loaded potentiometers, a joystick, an accelerometer, two channels of sonar and a video camera. The instrument requires significantly more physical input than a traditional violin, and for this reason, such instruments are often said to engage a performer's tactile sense. However, there is a missed opportunity, vaguely acknowledged in the addition of a spring-loaded potentiometer, of haptic feedback. A traditional violin had no more than to rely on its physical structure to generate haptic feedback – electronic additions are inherently non-haptic.

Novel Controllers

A novel instrument with an even greater claim to tactile engagement is the 'reacTable*' (Jorda et al. 2005). It is performed by moving differently shaped objects across a table. Their position is monitored from underneath the table and modular synthesisers are constructed according to the arrangement of more than one object. Real-time signal flow between objects is projected onto the table from underneath.

However, a performer moving a single block experiences the same haptic feedback for an entire performance despite hearing and seeing an almost infinite range of responses. The instrument itself judges the distance between blocks and assesses how strong the relationship is between them. This would seem to lend itself to haptic feedback which could reduce the necessity for other less intuitive control mechanisms.

Haptic Force-feedback

For the purposes of comparison with the proposed design of the Haptic Carillon, haptic force-feedback devices reviewed have been categorised according to whether they: a) use linear feedback, discrete feedback, or both; and b) whether they replicate an existing instrument or are a novel controller.

Linear and Discrete Feedback

This is a murky delineator, but one which is important to consider in the relationship between a performer and a device which uses force-feedback.

Figure 3 shows that most devices which exhibit linear feedback are replicas of existing instruments. This is because an existing instrument will most likely exhibit linear characteristics, that is, behaviour which is continuous between defined limits rather than discrete, or switching between two binary states.

Often, though, a haptic device will feature some combination of the two, creating a linear system interaction which can be augmented with discrete haptic cues.

Linear Feedback

The 'Haptic Turntable' (Beamish 2004) is a replica of a standard record player as would be used by DJs. A motor is used to rotate a solid disc onto which the DJ can apply backward or forward force. An optical sensor identifies the direction and velocity of the DJ's action and adjusts the feedback to allow the disc to 'slide' in a controlled manner, similar to a real turntable. The DJ's actions also control the playback of the audio.

The standard functioning of the device is reasonably linear. The haptic force-feedback is primarily defined by the velocity of the disc and the velocity and force of the DJ's action. The turntable will exert the same degree of resistance at the same speed each time it is used.

Discrete Feedback

The 'Haptic Turntable' delivers other feedback cues on top of the linearity of the entire device's haptic response.

The turntable is part of a larger system; this system analyses the audio being played and finds certain markers. These include strong beats, repeat lengths and density of texture in the music. This information is conveyed using haptic feedback forces extraneous to the normal operation of the rotary feedback when spinning backwards or forwards.

The developers of the turntable report that DJs were impressed with the accuracy of the haptic rotary response. However, most DJs surveyed found that they did not particularly use the discrete feedback. This was primarily because they were comfortable using other senses to ascertain information which was now interfering with the haptic response to which they are accustomed.

Replica Instruments - Novel Controllers

This response is at the core of the problem when augmenting a replica of an existing instrument with extra haptic cues, no matter how well intentioned. This is not so great a problem when creating a novel haptic interface.

The 'PHASE' project described earlier in this paper is an example of a new haptic interface for the performance of music. The instrument provides linear haptic feedback through a force-feedback arm consistent with the player's progression through a three dimensional terrain. The player's primary objective is to chase a computer generated object although they can veer from the most direct path in order to explore different textures and sounds. Each haptic response is appropriate to the visual world. However, the musical response changes depending on the current position of the music track.

In this case, a player's control over the music is mapped to parameters rather than a static, or discrete, representation. As the metaphor is a novel one, a player does not approach the instrument with any preconceptions, and the variability in music production creates no perceptual problems.

Conclusion

The above examples demonstrate the delicate nature of engaging a performer using haptic force-feedback. Perry Cook (2004) observed that humans are especially critical of reproductions of the voice because it is a replica of an instrument they have "years of experience playing".

In the case of the carillon, a practice instrument based on haptic principles will address a problem that has always been associated with that instrument. The carillon is one of the most public of instruments, perhaps the first means of broadcasting music. Being able to synthesise the sound of an instrument in a way that responds to the touch of the performer will allow carillonists to practice their art using headphones prior to public recital.

We are in the process of identifying an approach that will lead to the development of a practice carillon based on the principles discussed in this paper. Many of these are often regarded as self-evident by the musicians who play conventional instruments.

The challenge lies in isolating and identifying principles at work when performers play an instrument.

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