2009

The carillon and its haptic signature : modeling the changing force-feedback constraints of a musical instrument for haptic display

Mark Havryliv
University of Wollongong, mh675@uowmail.edu.au

F. Geiger
University of Wollongong, Florian.Geiger@iwb.tum.de

M. Gurtler
University of Wollongong, matthias-guertler@gmx.de

Fazel Naghdy
University of Wollongong, fazel@uow.edu.au

Greg Schiemer
University of Wollongong, schiemer@uow.edu.au

Publication Details

This conference paper was originally published as Havryliv, M, Geiger, F, Gurtler, M, Naghdy, F and Schiemer, G, The carillon and its haptic signature : modeling the changing force-feedback constraints of a musical instrument for haptic display, Proceedings of 4th International Conference, Haptic and Audio Interaction Design 2009, Dresden, Germany, September 2009. M. Ercan Altinsoy, Ute Jekosch and Stephen Brewster (Eds.). Springer-Verlag Lecture Notes in Computer Science, 5763, pp. 91-99.

The Carillon and its Haptic Signature: Modeling the Changing Force-Feedback Constraints of a Musical Instrument for Haptic Display

Mark Havryliv[1], Florian Geiger[1], Matthias Guertler[1],
Fazel Naghdy[1] and Greg Schiemer[2]

[1] Faculty of Informatics, and [2]Sonic Arts Research Network
University of Wollongong, NSW, Australia
mhavryliv@gmail.com, Florian.Geiger@iwb.tum.de
{mrg059, fazel, schiemer}@uow.edu.au

Abstract. The carillon is one of the few instruments that elicits sophisticated haptic interaction from amateur and professional players alike. Like the piano keyboard, the velocity of a player's impact on each carillon key, or baton, affects the quality of the resultant tone; unlike the piano, each carillon baton returns a different force-feedback. Force-feedback varies widely from one baton to the next across the entire range of the instrument and with further idiosyncratic variation from one instrument to another. This makes the carillon an ideal candidate for haptic simulation. The application of synthesized force-feedback based on an analysis of forces operating in a typical carillon mechanism offers a blueprint for the design of an electronic practice clavier and with it the solution to a problem that has vexed carillonists for centuries, namely the inability to rehearse repertoire in private. This paper will focus on design and implementation of a haptic carillon clavier derived from an analysis of the Australian National Carillon in Canberra.

Keywords: Haptics, musical instrument, physical modeling.

1 Introduction

1.1 Haptics in Musical Instruments

It has been conclusively demonstrated that musicians and sound-makers depend heavily on their haptic interaction with a sound-producing device; it has also been demonstrated that performers are 'trainable', with an inherent capacity to learn new haptic cues and use employ them in musical performance of novel instruments [1]. Indeed, novel instruments incorporating some form of haptics are increasingly pervasive as the barrier to entry for hardware and software is lowered [2].

However, sophisticated haptic implementations of traditional musical instruments are less common. The TouchBack piano [3], the V-Bow [4], the D'Groove [5], the MIKEY project [6], and the Haptic Drumstick [7] are notable examples of the few traditional instruments rendered specifically as haptic devices. Even rarer are attempts at applying haptic principles in realising instrument designs specifically designed to help train musicians in the performance of a traditional instrument.

In the authors' opinion, the greater research focus on haptics in novel, non-traditional devices is due to both legitimate interest in augmenting conventional instruments and creating new ones in order to extend the capabilities of electroacoustic performance, and the problems associated with recreating and simulating traditional instruments. These difficulties range from gathering information about the dynamic behavior of a traditional instrument to building a satisfactory prototype that has the 'feel' a seasoned instrumentalist expects.

A haptic incarnation of a traditional instrument, built for the purpose of practice or honing musicianship skills, must perform to the constraints of the real instrument. Further, a haptic instrument needs to replicate the visual, mechanical and sonic characteristics of the manipulandum – the point at which haptic interaction occurs between the musician and the instrument.

1.2 The Carillon Problem

The Haptic Carillon project is motivated by the possibility that the haptic and sonic characteristics of any carillon in the world can be simulated. To this end, an analysis of the haptic and sonic properties of the National Carillon in Canberra, Australia [8], has been undertaken, and these features have been statistically modeled.

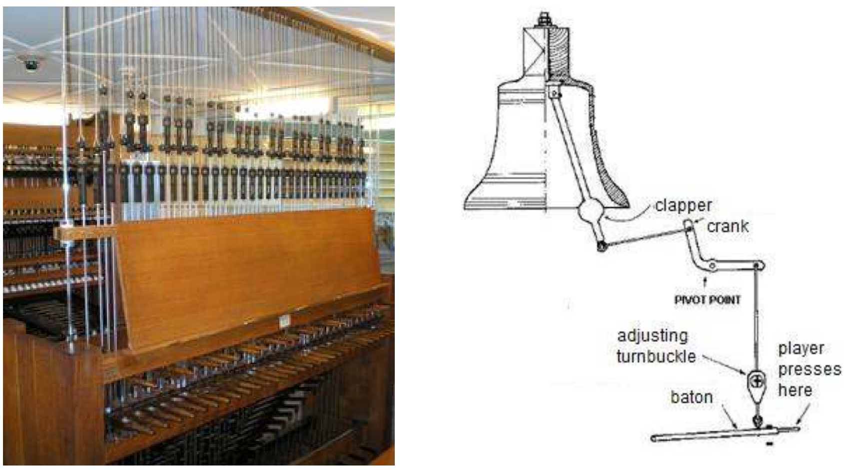

Fig. 1. (a) the carillon keyboard – National Carillon, Canberra, Australia
(b) simplified representation of the carillon mechanism

A carillon (Figure 1) is a mechanical construction with bells of various size played by a carilloneur from a mechanical keyboard, or clavier, housed beneath the bell chamber. It represents a particularly difficult haptic/sonic problem.

The carillon exhibits a mechanical complexity comparable to the piano, but where the piano aims at a consistency of haptic response across the entire instrument the carillon is predicated upon the idea that each key requires a different degree of force to play. These forces vary widely across the instrument, and are subject to seasonal variation.

The sonic response of the carillon is also subject to change over time; while bell, and carillon, sound synthesis is a well-established research area [9, 10], it is just as conclusively recorded that the sonic output of carillon bells change significantly over time [11]. What is less well-established is that the haptic behavior of a carillon also changes over time. This change is in no way linear or predictable, and it is not necessarily related to a change in the sonic behavior of the carillon.

The need for carilloneurs to develop musicianship and extend the instrument's repertoire offers a compelling musical reason to build a haptic practice instrument. Unlike other traditional instruments, the carillon, always has an audience, willing or unwilling, even if the carilloneur is only trying to practice.

We have developed the concept of a haptic signature as a way of acknowledging that a single type of instrument might have a variety of haptic behaviours, each of which it is important to replicate if the instrument is itself to be haptically rendered.

2 The Carillon Mechanism

The National Carillon in Canberra, located in a tower on Aspen Island in Lake Burley Griffin, houses 55 bells spanning four and a half octaves. Each bell weighs between seven kilograms and six tones. Despite the carillon's imposing mechanical construction its kinematic configuration is relatively straightforward.

Figure 1(b) is a simplified representation of the mechanism for one of the batons used to play the instrument. In its détente position, each baton rests against one of two beams that run horizontally across the range of the clavier, the upper beam for 'black' notes the lower for 'white' notes; in this position, the clapper on each bell is held away from the inside rim of the bell.

The bell clapper is connected to the baton via the bell crank. When a player presses downward on a baton, the clapper is pulled toward the inside of the bell. Between the upper and lower bells there is considerable variation in the force required to displace the clapper from its détente position. Measured at the tip of the baton this force is from 20-30 Newtons for the lower bells to 1-3 Newtons for the upper bells. This variation is continuous across the range of the clavier but is not linear; bell 4, for instance, requires 6N to displace the baton where bell 28 – at the halfway point in the keyboard – requires 1.3N. This component of the National Carillon haptic signature is shown in Figure 2.

2.1 The Haptic Signature

This variation can mostly be explained in terms of different clapper masses for different sized bells and difference in the length of the clapper stems and the crank masses for each bell. However, differently configured springs in most baton mechanisms can significantly mitigate or exaggerate the differences in clapper mass, as well as different levels of friction in respective bells.

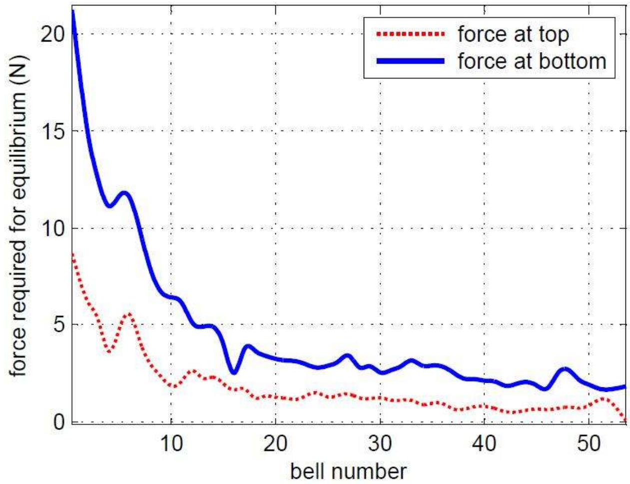

Fig. 2. Change in force required to bring the carillon system to static equilibrium across the range of batons in the National Carillon, Canberra. The displacement from the baton at the top of its stroke to the bottom is approximately -5cm.

It is clear in the above figure that the change in force required to play a baton is not linear, or even monotonic, across the range of the carillon. This graph, however, is the haptic signature of the instrument, and must be accommodated in any physical or statistical model. For the purposes of further modelling, we particularly note the difference between the force required at the top of the baton stroke and that required at the bottom of the stroke.

2.2 Notes on Data Collection

A difficulty faced in kinematic analysis of the carillon is the inaccessibility of a clear majority of the bells. Precise geometric measurements are taken of one of the heaviest but more accessible bells (bell 4) and masses are estimated based on bell's geometry and the density of the material, which for cast iron grey is 7.15 g/cc. Even much of this bell is difficult to measure, but solvable using trigonometry. We have taken the general kinematic form of bell 4 as a model for all other bells, although there are several small differences.

A hand-held spring gauge is used to broadly determine static equilibria in different bells measured at different parts of each bell. Spring gauge also helped verify mass estimates and calculate *k* values for different springs.

An inertial measurement unit[1] is also used to measure a baton's dynamic response to different applied forces and initial states. The mathematical models shown below are verified against both the static forces measured with the spring gauge and the baton motions measured in response to different forces.

[1] XSENS MTi – http://www.xsens.com

2.3 Dynamic Analysis and Modelling

For the purposes of analysis, the carillon model is divided into three rotational sub-models, each of which interacts with the other through reaction forces, otherwise interpreted as the tension in the two cables that join the 1) clapper system to the crank system, and 2) crank system to the baton system. While these cables retain some tension (as they do throughout normal operation of the carillon), it is possible to define reasonably straightforward equations of motion for the respective rotational systems

As the acceleration of the entire system is uniform, it is relatively simple to hold the dynamical properties of the baton and crank sub-system stable whilst changing the clapper sub-system properties to match the observed static and dynamical behaviour.

2.3.1 Baton and Crank

Figure 1 shows that the baton and crank are reasonably straightforward rotational systems: as the entire system experiences uniform acceleration due to the constant tension in the connecting cables T_B and T_C, it is possible to calculate from:

$$I\ddot{\theta}_{Baton} + \frac{L_{Baton}(T_B - b\theta_{Baton})}{2} - \tau_{Baton} - F_P L_{Baton} = 0 \quad (1)$$

where:

$$\tau_{Baton} = \frac{gsin\theta_{Baton}L_{Baton}}{2}(m_{Baton} + m_{Cable}) \quad (2)$$

and

$$I\ddot{\theta}_{Crank} - \tau_{Crank} + T_C r - T_B r \quad (3)$$

where

$$\tau_{Crank} = gr/2(\cos(\theta_{Crank} + 90)\, m_1 + \cos(360 - \theta_i + \theta_{Crank})m_2) \quad (4)$$

and where F_p is the force exerted by a player at the tip of the baton, and m_1 and m_2 are the masses of the rods constituting the crank (Figure 3).

2.3.2 Clapper System

The clapper system consists of three masses: the clapper, and two rods; the first rod attaches the clapper to a pivot inside the bell while the second attaches the clapper to cables that link it to springs, rubber dampers, and the crank system.

The equation of motion for the clapper in free movement is given simply as:

$$I\ddot{\theta}_{Clapper} - \tau_{Clapper} + T_C L_{Clapper} = 0 \quad (5)$$

where

$$\tau_{Clapper} = gsin\theta(\textstyle\sum_{i=1}^{3} m_i L_i) - k\theta_{Clapper}, \quad (6)$$

where $m_i L_i$ are the masses and the respective distances from their centres of gravity to the pivot point.

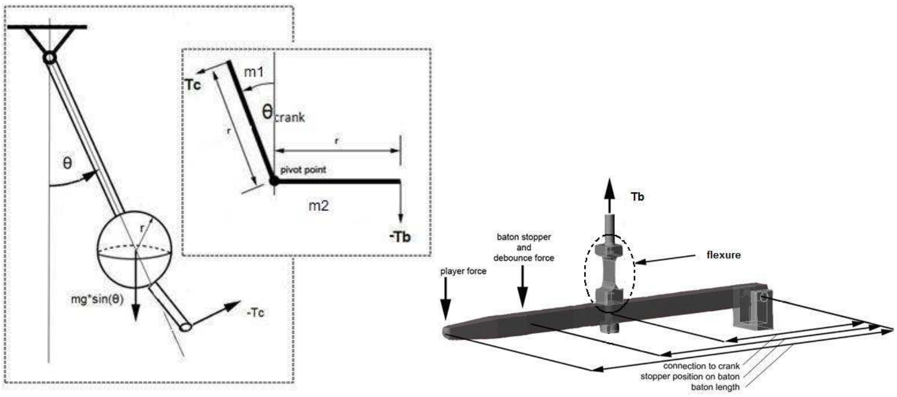

Fig. 3. (a) Clapper and crank sub-systems, (b) baton sub-system

I is the sum of the moments of inertia of the masses, k is the angle-dependent force applied by the spring where the sign of k is determined by the direction of spring - forward or return and $T_C L_{Clapper}$ is the product of the tension in the cable linking the bottom of the clapper rod to the tip of one of the crank bars and the distance to the pivot. T_C includes all the force applied by the tendency of the crank to rotate the clapper toward the bell and any force applied by a player. The clapper's change in angle is only very small, typically less than 4 degrees.

Clapper Impacts

The clapper system also includes two impact forces that are applied when displacement constraints are violated: the first of these is impact from the inside of the bell wall, forcing the clapper counter-clockwise; the second is impact from the rubber stopper that is coupled to the lower rod with a cable and stops the clapper from rotating further counter-clockwise. It is important to model these impacts correctly as they are the principle determinants of the motion of the baton tip at its upper and lower extremities.

2.3.3 Change in Clapper Force – the Haptic Signature

As the clapper is the only sub-system of the carillon whose variables are changed from one baton to the next, it is useful to characterise the a) force; and b) change in force as felt by the user, as the boundary conditions and position-dependant coefficients in the clapper model. Although the clapper force is determined by a large number of variables, it is regularly shown that a post facto curve-fitting analysis reduces the change in force over change in angle can be to a single linear polynomial equation, i.e. two variables in place of at least four. This is intuitive when one recalls that a small change in sin(θ) is approximately equal to θ.

2.4 System Modelling

Applying the principle of uniform acceleration and calculating the relative accelerations between systems, it is possible to determine reaction forces at each cable connection and thoroughly model the dynamics of every bell in the National Carillon.

3 Models – Simulated and Measured Motions

The recorded motions of the National Carillon were measured using an inertial sensor are used to compare the performance of the analytically derived model against the real carillon. All the mathematical models are programmed and executed step-wise in the Simulink ODE solver (www.mathworks.com/products/simulink).

3.1 Bell 4

Bell 4 is particularly well modelled, as it was reasonably accessible for the purposes of obtaining geometric and force measurements. The following figures demonstrate the performance of the simulated model against the measured data. Two initial tests are taken: releasing the baton from the bottom of its stoke in order to measure the dynamics of the system without user influence (Figure 4), and releasing the baton from the top of its stoke with a mass attached in order to measure the system's response to applied force (Figure 5).

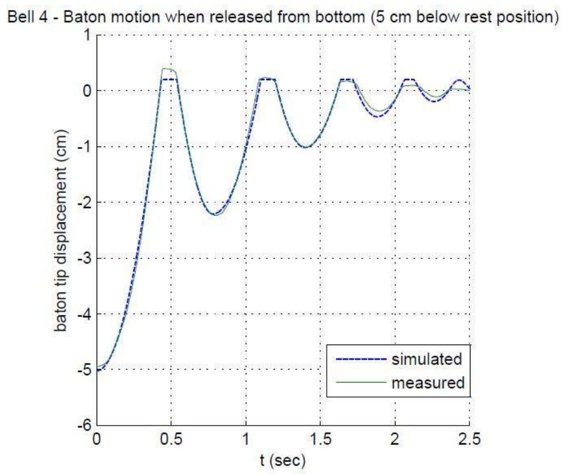

Fig. 4. Performance of the simulated model against measured data. The baton is held to the bottom of its stroke, then released.

It can be seen there is very little error between the simulated and measured data. This is supported by a static analysis of this bell in which forces recorded in Figure 2 are applied to the mathematical model and found to match the behaviour of the real carillon, i.e. finding equilibrium at the top and the bottom for the respective forces.

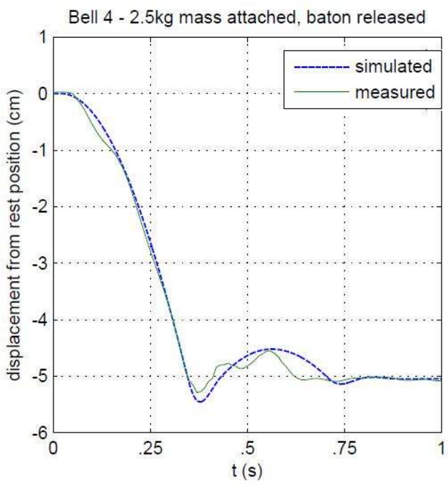

Fig. 5. 2.5kg mass attached to the baton for bell 4 and released from top.

3.2 Bell 7 and 10

This method is proven for other bells; bells 7 & 10 modelled in Figure 6.

Note that the motions for bells 7 and 10 are quite different; in fact, bell 10 is a lot more similar in motion to bell 4 than it is to bell 7. The time is takes each baton to come to rest is a direct function of the difference in force required to stabilise the baton in different position as shown in Figure 2.

4 Prototype and Audio

The dynamic analysis presented in this paper is the basis for the haptic carillon prototype pictured below. The mathematical model is arranged such that it can be solved in real time using forward dynamics, i.e. the system's motion in response to forces. It is programmed in Simulink and compiled to run on a standalone target PC which connects to an electromagnetic linear actuator through a dedicated analog I/O board.

This actuator controls the position of the baton, and back-EMF at the actuator windings is measured in order to close the feedback loop by determining the force applied by the player.

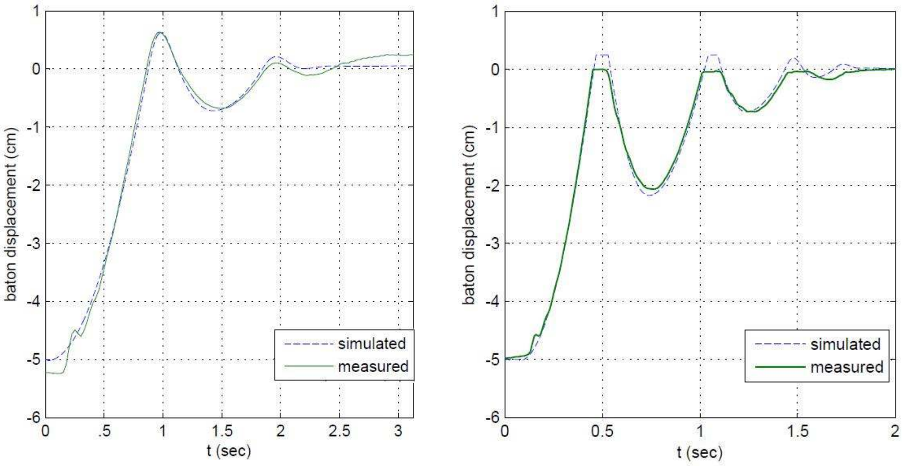

Fig. 6. Bells 7 and 10 modelled.

Fig. 7. The haptic carillon single-baton prototype

4.1 Audio

Fortunately, the problem of generating appropriate sound synthesis is somewhat mitigated in this environment. Typically, a carillonneur only hears their instrument through loudspeakers amplifying the signal picked up by strategically-positioned microphones in the bell tower. The National Carillon, for example, provides only this type of aural feedback to the performer. The insulation of the playing room from the bell tower is very thorough.

The authors have recorded the carillon bells directly from these microphones, and by carefully mapping the velocity at which the baton was travelling when hitting the bell (propelled with a motor attached to a tachometer, and recorded at 15 velocities per bell) to the recorded sound, it has been relatively straightforward to design a playback mechanism in pure-data that mixes the samples together based on the velocity with which a player had the clapper strike the bell. User-testing thus far indicates that carillonneurs are unable to distinguish between this method of sample playback and the amplification of an actual carillon bell signal in the tower.

5 Conclusion

Future user-testing will build on current haptic research to assess the nature of a performer's perception of a traditional instrument against this haptically rendered one. A particularly interesting avenue of enquiry will be researching the extent to which high-fidelity audio synthesis can mitigate low-fidelity haptic interaction – and vice versa – in the context of a replica of a traditional musical instrument.

References

1. O'Modhrain, S.: Playing by Feel: Incorporating Haptic Feedback into Computer-based Musical Instruments. Stanford University, Stanford (2000)
2. Berdahl, E., Steiner, H. C., and Oldham, C.: Practical Hardware and Algorithms for Creating Haptic Musical Instruments. In Proceedings of New Interfaces for Musical Expression (2008)
3. Gillespie, B.: Haptic Display of Systems with Changing Kinematic Constraints: The Virtual Piano Action. Stanford University, Stanford, (1996)
4. Nichols, C.: The vBow: A Virtual Violin Bow Controller for Mapping Gesture to Synthesis with Haptic Feedback. In Organised Sound Journal (2002)
5. Beamish, T., Maclean, K., Fels, S.: Designing the Haptic Turntable for Musical Control. In Proceedings of 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, IEEE (2004)
6. Oboe, R.: A Multi-Instrument, Force-Feedback Keyboard. In Computer Music Journal, vol 30, no. 3 (2006)
7. Berdahl, E., Verplank, B., Smith III, J. O., Niemeyer, G.: A Physically-Intuitive Haptic Drumstick. In Proceedings of International Computer Music Conference, Copenhagen, Denmark (2007)
8. National Carillon, Wikipedia http://en.wikipedia.org/wiki/National_Carillon
9. Karjalainen, M., Esquef, P., Valimaki, M.: Making of a Computer Carillon. In Proceedings of Stockholm Music Acoustics Conference, Stockholm, Sweden (2003)
10. Fletcher, N.H., Rossing, T. D.: The physics of musical instruments. Springer-Verlag, New York (1991)
11. Fletcher, N. H., McGee, W. T., and Tanopolsky, A. Z.: Bell clapper impact dynamics and the voicing of a carillon. In Acoustical Society of America 111(3): 1437-1444 (2002)