Haptic Carillon – Analysis & Design of the Carillon Mechanism

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Abstract

The carillon is one of the few instruments that elicit 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, force-feedback, mechanical analysis.

1. Introduction

1.1 Haptics in Musical Instruments

The capacity for haptic interaction has become increasingly important in the field of expressive instrument design. The ease with which force-feedback may be incorporated using new sensors and actuators has led to a profusion of novel musical instruments that engage the sense of touch. O'Modhrain demonstrates that musicians rely heavily on haptic interaction with a sound producing device, and how novel instruments are often able to 'train' a performer to anticipate a particular haptic feedback produced within the constraints of hardware or software [1].

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The expressive application of force-feedback has been applied in a number of novel instruments, most notably the Touchback Piano [2], the V-Bow [3], the MIKEY project [4], the D'Groove [5] and sound editor [6].

Haptic designs fall into two categories; the first of these replicate or augment the capabilities of conventional instruments as demonstrated in work of Gillespie, Nichols , O'Modhrain and others; the second includes designs that explore and engage with expressive features of new technology as summarised in Berdahl, Steiner and Oldham [7]. However, few attempts have been made to apply haptic principles in realising instrument designs for training traditional performers.

This is due partly to the focus on either augmenting conventional instruments or the creation of new ones in order to extend the capabilities of electroacoustic performance, but principally due to problems associated with recreating and simulating traditional instruments. These difficulties include gathering information about the dynamic performance of a traditional instrument and 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 and mechanical characteristics of the manipulandum – the point at which haptic interaction occurs between the musician and the instrument.

1.2 The Carillon

A carillon is a mechanical construction with bells of various size played by a carilloneur from a mechanical keyboard, or clavier, housed beneath the bell chamber.

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 tonnes.

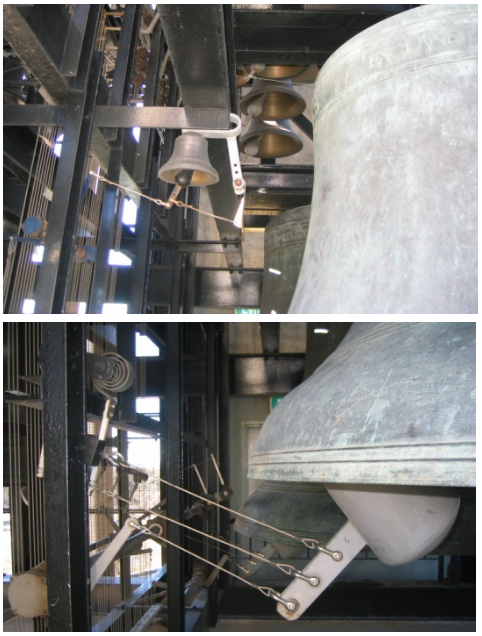

Figure 1.a (top) Bell 54 is the small bell (left) shown next to bell 4 (right); note the spiral torsion spring pulling the clapper away from the inside of bell 54. Figure 1.b (bottom) also shows bell 4; note the spring pulling the clapper toward bell 4.

1.3 Haptic 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.

A haptic carillon model needs to represent different forces applied on different batons. These forces vary considerably depending on the size of the bell and therefore the mass of the clapper that has to moved in order to play it; they also depend on the length of the clapper stem, the size of the return spring (in larger bells) and the tension of the guy ropes connecting the baton to the bell crank.

Unlike other traditional instruments the carillon is constantly exposed to the elements and its mechanical response is also subject to wide variation in temperature. The haptic model therefore needs to be adjusted easily to simulate differences in the response of each baton across the entire range of the same instrument. And because corresponding batons on different carillons do not necessarily respond uniformly to applied pressure, a haptic model must also represent the idiosyncracies of individual carillons.

2. The Carillon Mechanism

Despite the carillon's imposing mechanical construction its kinematic configuration is relatively straightforward. Figure 3 is a simplified representation of the mechanism for one of 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 as shown in Figure 1a and 1b.

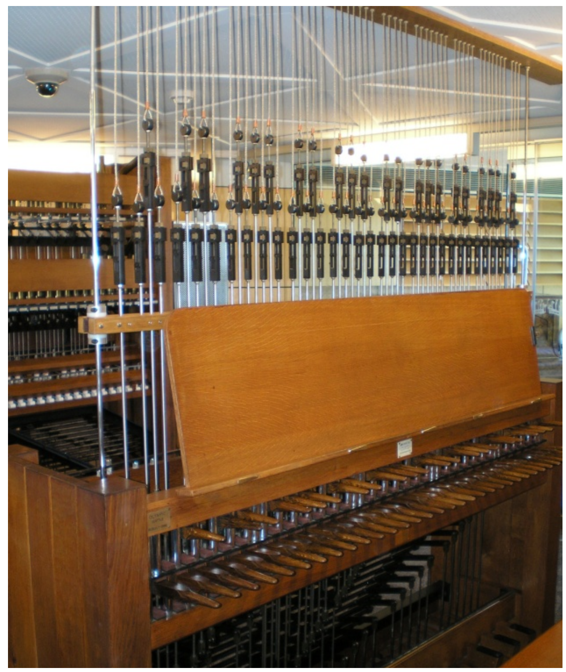

Figure 2 shows batons laid out in the same chromatic keyboard arrangement as a piano with guy ropes connecting each baton to a bell crank and clapper located in the bell chamber overhead.

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 10N to displace the baton where bell 28 – at the halfway point in the keyboard – requires less than 3N.

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.

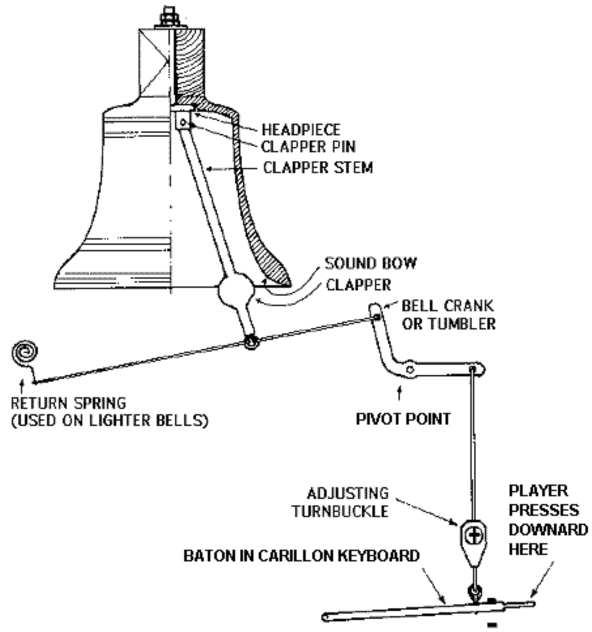

Figure 3. This carillon mechanism (in détente position) shows the mechanical interactions that constitute the forces felt by a player.

2.1 Return and Forward Springs

The mechanical configuration shown in Figure 3 shows a return spring attached to the clapper. From this diagram it is possible to conceptualise that the spring pulls the clapper away from the inside of the bell wall, effectively applying a restorative force which is felt by the player as resistance at the baton tip.

The return spring is used to ensure that the clapper and baton return to the détente position and effectively smooths the change in force felt by the player. Each spring applies a different restorative force proportional to the force required to pull the clapper back to its détente position. Each spring also plays its part in producing gradual change in the response of batons across the range of the clavier.

As indicated in Figure 1 the return spring is only used on lighter bells. In the National Carillon the heavier bells (1-27) use a forward spring to assist the player by pulling the clapper against the inside of the bell wall. Without forward springs these bells would be unplayable. With the forward spring attached a force of 155 Newtons is required to hold the clapper against bell 4; with the forward spring attached, the force required is between 75 - 90 Newtons, depending on the position of the clapper.

In the National Carillon, bells 35-55 use return springs, though almost negligible force is required by bells 35-40 while bells 28-34 do not use springs.

3. Dynamic Analysis

The carillon mechanism can be analysed as three coupled rotational systems exchanging forces: the clapper system, the crank system and the baton system. A physical model is then created that models the motion of each of these systems and determines the forces felt at the tip of the baton. [2], [3], [4], and [8] are early demonstrations of the suitability of this method for the replication of motion and forces in mechanical systems.

3.1 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.

3.2 Clapper System

The clapper system consists of three masses: the clapper (m_2) and two rods; the first rod (m_1) attaches the clapper to a pivot inside the bell while the second (m_3) attaches the clapper to cables that link it to springs, rubber dampers, and the crank system. While the geometric measurements of the clapper and clapper position relative to the pivot are only approximations for some bells, it is still possible to make several generalisations that will apply in the case of all bells in the carillon.

The mechanism for bell 4's clapper is shown in Figure 4; all forces external to this mechanism, other than clapper impact with the bell, tend to rotate the clapper counter-clockwise. Lighter bells have a force term pulling the clapper clockwise away from the bell.

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

$$I\ddot{\theta}_{Clapper} - \tau_{Clapper} + T_C L_{Clapper} = 0, \qquad (1)$$

where

$$\tau_{Clapper} = g\sin\theta\left(\sum_{i=1}^{3} m_i L_i\right) - k\theta_{Clapper}, \qquad (2)$$

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

[1] XSENS MTi – http://www.xsens.com

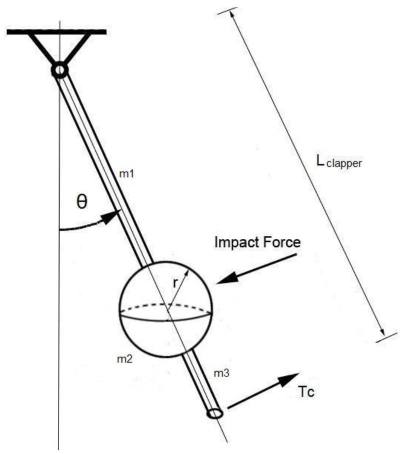

Figure 4. Simplified clapper mechanism.

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 change in angle of the clapper system is very small, less than 2 degrees.

3.2.1 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.

3.3 Crank System

The crank system consists of two rods attached to a pivot point; one rod connects to a cable linked to the lower clapper rod, and the other to a cable liked to the baton.

The equation of motion for the crank system is:

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

where

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

where θ_i is the angular offset of the crank connected to the clapper.

I is the sum of inertias of the two crank bars, T_C is the tension in the cable going to the clapper and T_B is the tension in the cable going to the baton. The magnitude of the crank rotation is approximately 24 degrees.

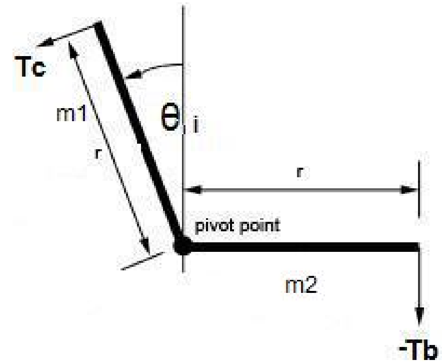

Figure 5. The crank mechanism. The player applies force through a link to the baton at the far right of the crank.

3.4 Baton System

The baton rotates very slightly – approximately 12 degrees – around a pivot point at the non-playing end. A rod midway along the baton is coupled to a cable which then links the baton to the crank, doubling the player's mechanical advantage. A thin tempered steel coupling called a flexure (shown in Figure 6) allows the rod to remain perpendicular to the détente position of the baton at all times even when the baton is pressed downwards. A strip of thick felt is also used to reduce friction between the wooden retaining structure and the moving rod as it moves up and down. Some friction still occurs between the moving rod but it is modelled as a function of baton position. But it is not baton position but deformation of the flexure that pushes the metal rod against the felt strip.

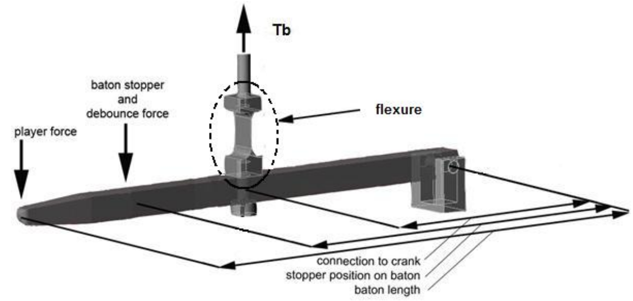

Figure 6. The flexure (highlighted) midway between the baton tip and baton pivot.

The baton is also a relatively simple mechanism; the only torque about the pivot is the mass of the baton, the mass of the flexure/cable element, the tension in cable T_B and the force F_P applied by the player at a distance L_{Baton}. The equation of motion includes these forces and the friction due to felt:

$$I\ddot{\theta}_{Baton} + \frac{L_{Baton}(T_B - b\theta_{Baton})}{2} - \tau_{Baton} - F_P L_{Baton} = 0 \quad (5)$$

where:

$$\tau_{Baton} = \frac{g \sin\theta_{Baton} L_{Baton}}{2}(m_{Baton} + m_{Cable}) \quad (6)$$

and b is a small value that allows for approximately 5N at the baton's maximum displacement (measured with a tactile force sensor).

3.5 Entire System

The three mechanical subsystems are coupled using stiff wound cable. The cable between the clapper and crank is always tensed, and during normal usage the cable between the baton and the crank is tensed. (The term 'normal usage' assumes the player applies only downward force on the baton. Intuition and observation confirm this usage model.)

For most of the motion of the baton, each subsystem exhibits uniform angular acceleration. The only exception is when the baton is fully displaced from its détente position and the clapper/crank system continues moving until the clapper hits the bell – this is similar to a piano action where the hammer is in free-flight toward the string after the piano key is fully depressed. This state is characterised as a loss of tension in the cable between the baton and the crank.

3.5.1 Clapper/Crank System

The cable coupling the crank and clapper is always tense, therefore the angular acceleration of the crank and clapper is always equal. Therefore, we can solve for the acceleration of this system around one pivot point by proportionately including the forces applied through the tension of the cable. This proportion is defined as:

$$\ddot{\theta}_{Clapper} = -\frac{L_{Crank}}{L_{Clapper}}\ddot{\theta}_{Crank} \qquad (7)$$

Solving (1) and (3) for their respective angular accelerations, then substituting into (7), and setting the co-ordinate frame such that $\theta = 0$ when the right crank rod is perpendicular to the y-axis , we get:

$$\frac{\tau_{Clapper} - T_C L_{Clapper}}{I_{Clapper}} = -\left(\frac{L_{Crank}}{L_{Clapper}}\right)\frac{\tau_{Crank} + L_{Crank}(T_B - T_C)}{I_{Crank}} \qquad (8)$$

Solving (8) for T_C whilst setting T_B to 0 – i.e. no force applied by the baton –, then substituting T_C into (3), and the resulting expression solved for $\ddot{\theta}_{Crank}$ into (7) gives the angular acceleration for the clapper, and, therefore, the clapper/crank system.

3.5.2 Baton System Coupling

The baton system is coupled to the crank with a flexible vertical cable. As a result any force in the baton system tends to rotate the crank counter-clockwise. This means that whenever the sum of torque on the baton pivot is negative (↓y, clockwise), all three subsystems exhibit uniform angular acceleration defined by:

$$\ddot{\theta}_{Clapper} = -\frac{L_{Crank}}{L_{Clapper}}\ddot{\theta}_{Crank} = -\frac{L_{Baton}/2}{L_{Clapper}}\ddot{\theta}_{Baton} \qquad (9)$$

By substituting (1) and (5) into (9) and removing the crank acceleration term, then removing T_C by solving for T_B and then following the substitutions in §*3.5.1*, the uniform angular acceleration of the entire system is found.

When the sum of torque about the baton is positive, and the baton tends counter-clockwise, tension between the baton and crank is lost, and the angular acceleration of the baton is separate to that of the crank/clapper system. This remains the case until torque is once again positive, and the natural length l of the cable between the baton and crank is reached.

4. Results

The results produced in the experimental work show the behaviour of the mathematical model under the same initial conditions as bells measured at the National Carillon. The model is a set of ODEs realised in Simulink (Matlab)[2]. It takes force at the baton tip as the input, and baton angle as the output. The three subsystems are modelled separately, but constant tension between all couplings is assumed and angular acceleration is calculated about the crank pivot. Each system is integrated separately; in the case of a loss of tension each subsystem will continue to calculate its unique displacement.

A comprehensive model has been simulated based on three bell types: forward spring bell (4), no spring bell (28), and return spring bell (41).

The simulation is initialised with the baton being held, then released, from a baton's maximum displacement. The baton moves to the top of its stroke, is repelled by both the felt-covered wooden beam, and the impact of the rubber stopper and the clapper rod, and eventually comes to rest in its détente position – shown in Figure 3.

4.1 Bell 4 – Forward Spring

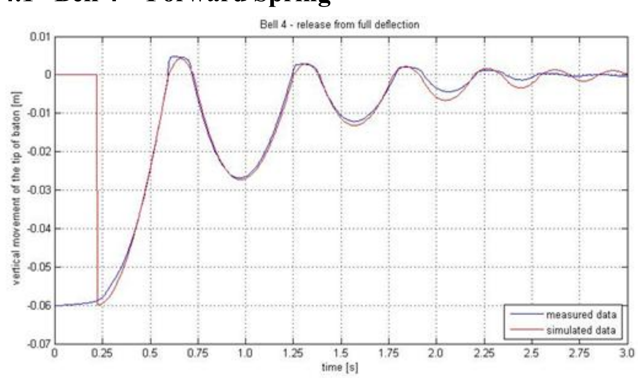

Figure 7. Simulated and measured data for bell 4

Bell 4 is one of the few bells in the chamber where accurate geometric measurements are possible. From these measurements a model for each bell was constructed. This model also provides convincing simulations of the debounce motion that one observes in the actual carillon.

[2] http://www.mathworks.com/products/simulink/ & http://www.mathworks.com/products/xpctarget/

4.2 Bell 28 – No Spring

The model for bell 28 is based on the geometry of bell 4, with an across-the-board decrease in system masses, and the removal of the forward spring. The forward spring in bell 4 is so powerful that the inevitable error in empirically measuring its *k* leads to slight simulation error. With the spring removed as a factor in bell 28, a significantly lower error is recorded in the initial free motion and debounce.

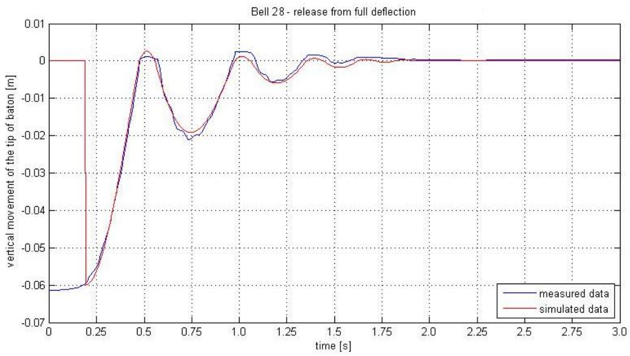

Figure 8. Simulated and measured data for bell 28

4.3 Bell 41 – Return Spring

Bell 41 is again modelled on the geometry of bell 4, drastically reducing the masses in the system and replacing the forward spring with a return spring. Simulating the free motion of this bell is almost trivially simple, as the force applied by the return spring is an order of magnitude greater than the sum of all other feedback forces.

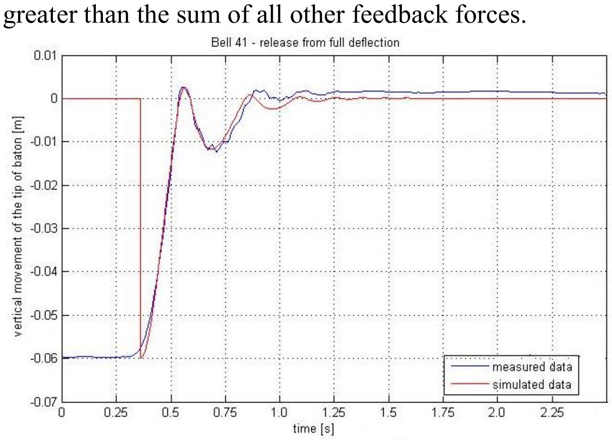

Figure 9. Simulated and measured motion of bell 41

5. Conclusion

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.

Work is being undertaken to develop an intelligent model for any carillon baton, removing the need to manually collect data for each, or indeed, most batons.

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.

Figure 10. Haptic baton prototype

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