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An Expressive Multidimensional Physical Modelling Percussion Instrument

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ABSTRACT

This paper describes the design, implementation and evaluation of a digital percussion instrument with multidimensional polyphonic control of a real-time physical modelling system. The system utilises modular parametric control of different physical models, excitations and couplings alongside continuous morphing and unique interaction capabilities to explore and enhance expressivity and gestural interaction for a percussion instrument. Details of the instrument and audio engine are provided together with an experiment that tested real-time capabilities of the system, and expressive qualities of the instrument. Testing showed that advances in sensor technology have the potential to enhance creativity in percussive instruments and extend gestural manipulation, but will require well designed and inherently complex mapping schemes.

1. INTRODUCTION

Electronic percussion, drum synthesis and drum machines date back to the late nineteen-thirties [1]. Since then, a variety of electronic percussion instruments such as the electronic drum kit, hand drum and trigger have been popularised or explored in an academic context. Examples include the ETabla [2], Roland Handsonic [3], Korg Wavedrum [4] and Roland V-Drum [1, 5]. The mentioned examples generally utilise sample-based synthesis and their interaction capabilities are mainly limited to striking or brushing the physical interface. In general, electronic percussion instruments can offer both advantages and disadvantages in comparison to their acoustic counterparts. Advantages include a low acoustic footprint, versatility, compactness and potential for advanced user interaction design. Disadvantages include velocity sensitivity issues, unresponsiveness to performance nuances and required amplification [6].

An important consideration in making digital percussion instruments and controllers is the need to be able to capture fast impact gestures. Acoustical percussion instruments are typically excited with an impact, producing a short burst of energy and a rich spectrum. The onsets are generally well defined, and once initiated the player has little control over the tone [7]. This does not, however, mean that interaction is limited to one type of impulse. Rather the combination of different striking implements, including fingers and palms, and the different shapes and materials that can be hit, stroked, pressed and dampened, result in a huge palette of percussive gestures [8]. By comparison, most digital percussive instruments capture the velocity and contact points of a stroke in a crude manner [9], thus reducing an important element of expressivity. Recent advances in sensor technology however, allow for nuances in percussive gestures to be captured more accurately, consequently improving interaction in digital percussion instruments. An example of this is the BopPad [10], which utilises *smart sensor fabric* to allow for velocity and radial position sensing.

With these advances, new sensors are able to provide a vast amount of useful information regarding input interaction. This wealth of information may be redundant for commonly used sampled-based synthesis approaches, but can prove effective for highly parametric synthesis methods, as found in physical models. Although inherently more complex and CPU heavy, physical models provide an attractive alternative to other synthesis methods since they allow for both faithful sound reproduction of instrument characteristics and also for a multitude of expressive possibilities. The harmony between developments in these two fields allow for digital instruments to extend beyond the sonic capabilities of their acoustic counterparts, whilst retaining or improving on gestural interaction.

As instruments based on this type of synthesis are complex and offer vast parametric control, designing an intuitive control system can be a difficult undertaking. A practical approach towards the design of instruments using physical modelling instruments is proposed in [11].

Within the New Interfaces for Musical Expression (NIME) community several interfaces designed to control physical models have been brought forward, including percussion instruments. Two of these in particular are relevant to the current work. For example, the PHYSMISM [12] is a physical modelling instrument that emphasises explorability and control. Users were provided with a modular instrument where they were able to combine inputs and outputs of physical models by coupling them, and mix instantaneous and continuous excitations with different resonators, creating a platform for extensive sound exploration.

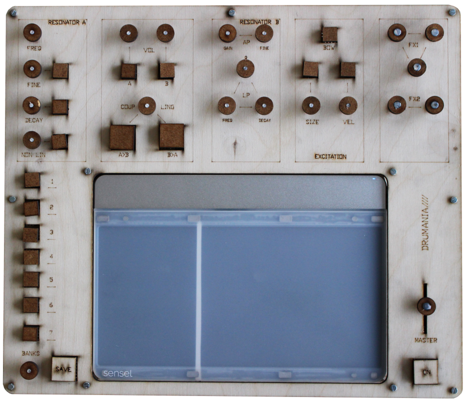

Figure 1. The percussion instrument, consisting of a custom made control surface with the Sensel Morph.

Chromaphone [13] is a unique commercialised synthesis engine dedicated to the creation of virtual acoustic instruments using physical modelling sound synthesis. It features resonator coupling for accurate descriptions of the exchange of energy between resonators, which allows for the synthesis of rich and natural sounds. The user selects two resonators, tweaks their parameters individually and can couple them at a certain intensity balance. Properties such as excitation stiffness, hit position, radius, material and decay are adjustable. This approach served as the basis for the control structure of the instrument.

In this paper we describe an instrument that aims to utilise efficient sound synthesis and recent developments in interaction design and hardware technology to create a novel percussion synthesiser. It can be best described as a percussive pad instrument with a hardware controller and integrated graphical user interface (illustrated in Figure 1). The pad itself is the Sensel Morph [14], which utilises advanced touch technology to provide high-resolution and accurate multidimensional input data. The audio and sensor processing are performed in Pure Data (Pd) which acts the central hub for running all software aspects of the instrument. The Morph and hardware controller are connected to Pd via two Arduino boards, the former of which utilises Sensel's API for retrieving input data. The physical modelling synthesis is based on the 2-dimensional Digital Waveguide Mesh (DWG) [15] and the Banded Waveguide (BWG) model [16] with some extensions such as the incorporation of a displaced bow model [17], which allows for unique continuous interaction and manipulation of percussive sounds. The backbone of the model is created in the functional programming language Faust [18], facilitating generation and conversion of Faust scripts to the Pd architecture. The general structure of the implementation is shown in Figure 2.

Interaction of the instrument takes particular inspiration from recent developments in multidimensional polyphonic expression (MPE), which is utilised by expressive instruments such as ROLI's seaboard and the LinnStrument [19], [20]. By combining the Morph's input data with extensive parametric control of the physical model, we have been able to replicate and extend aspects of MPE and tailor it towards percussive instruments. Specifically, the surface can be played polyphonically, by hitting, tapping or being continuously pressed - which allows the performer to shift and manipulate the model in a distinct way without further adjustments. We demonstrate that developments in sensor technologies have created an exceptional platform for creative control of physical models, and that traditional gestural interactions can be extended and improved with these advancements.

In the following we will describe the software and hardware implementation of the instrument in more detail.

2. AUDIO ENGINE

The percussion instrument uses an implementation of a BWG model plus a DWM as means of sound synthesis. As a member of the physical modelling family of algorithms, it allows full flexibility of its parameters and a natural sensibility to musical expressiveness, given the fact that no sample reproduction system is used. Figure 3 depicts the general overall architecture of the system that interconnects the different modules. An excitation generator, usually outputting a kind of impulsive signal is then followed by a parallel connection of the BWG module and the DWM module. Both receive the dry excitation signal and act as a resonator due to its many signal feedback loops, defining the main characteristics of the sound. The numerous parameters of both the BWG and DWM blocks are modulated in real time via the control signals provided by the user interface (Figure 1). Additionally, a parameter connects the BWG to the WGM and vice-versa to account for the energy transfer that takes place between different parts of a real physical instruments. This parameter is called Coupling. Finally, both output signals from the BWG and DWM modules are then fed into a post-processing unit. Figure 4 shows the the system block diagram the BWG module coupled to the WGM module.

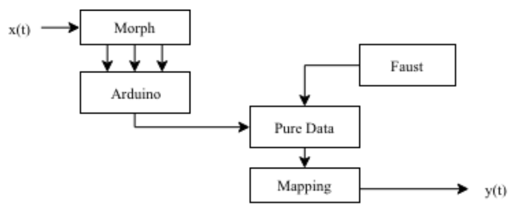

Figure 2. General implementation structure.

2.1 Faust: DSP

Faust (Functional Audio Stream) is a functional programming language designed specifically for real-time signal processing and synthesis. The Faust compiler is able to translate Faust programs into equivalent efficient C++ programs which can be used with Faust's audio architecture modules to compile to various environments such as Jack, Max/MSP, VST, SuperCollider, PD and JUCE.

We use Faust to build the digital signal processing algorithms on which the system is based. These are then ex-

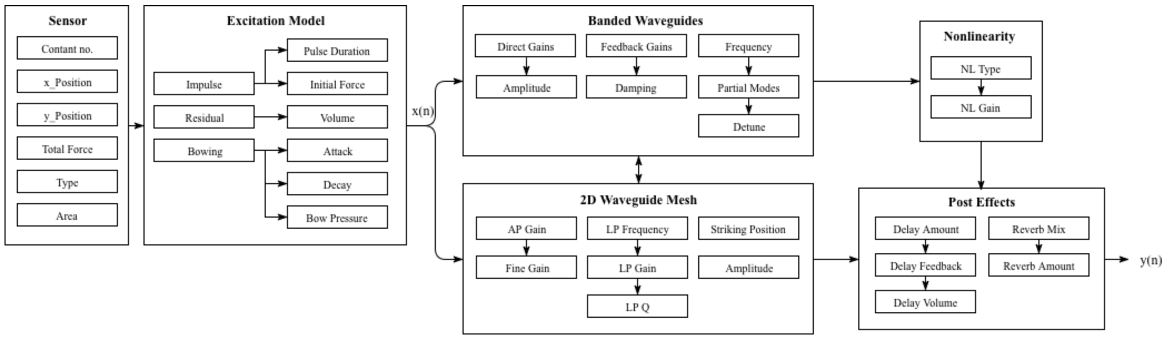

Figure 3. System architecture with internal parameters.

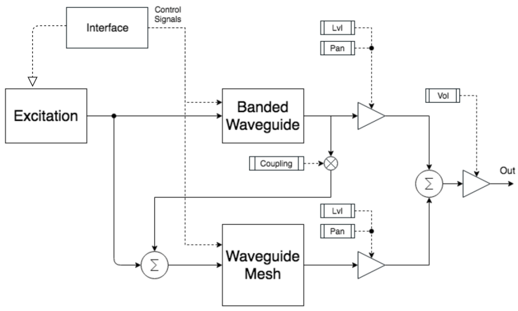

Figure 4. Block diagram of the system with a coupling of the BWG module to the WGM module.

ported to Pd as external objects with the `faust2puredata` module [21], so that Pd can be used as the audio engine and connection hub between all units of the system.

The `faust2puredata` script allows for generation of Pd abstractions as 'wrappers' around Faust units, meaning that the Faust control parameters are interfaced in an object in Pd's GUI as sliders, buttons, toggles and/or numbers.

The signal processing algorithms of the BWG, WGM and effects filters (delay unit and reverb) were obtained from the Faust-STK (Synthesis Toolkit) library [22], which is a translation from the C++ STK library [23]. They were then extended, parameterised and incorporated in Pd, the central signal processing hub.

2.2 The Banded Waveguide Module

As described in detail in [16], the BWG system is a bank of filters where each band represents a mode of the vibrating structure, a synthesis method similar to the modal synthesis approach where the excitation model excites a bank of resonant filters connected in parallel [24]. An advantage in using banded waveguides over modal synthesis is that the modes can be individually modelled whilst maintaining direct control of the vibrating structure in both time and space [25]. Each branch of the bank representing a resonant mode contains a narrow-band bandpass filter followed by a delay line (waveguide), where the output is then added to the other bands and also fed back into its respective band. A fine control over each frequency (or partial) is maintained by adjusting their amplitude (Direct gain) and decay over time (Feedback gains). These two parameter groups are material-dependent and provide the main acoustic characteristics of the sound being produced. A fast decay rate will be perceived as wood or glass, whereas a longer decay will make the sound resonate more and sound metallic as a result. Additionally, these parameters are associated with physical interactions between the musician and the instrument (such as damping), and are very useful in terms of enhancing expressivity of the instrument.

By arbitrarily setting vastly different delay times on each branch, usual comb filtering effects and Karplus-Strong-like sounds may appear, making the filter bank effectively behave like a set of N parallel waveguide synthesisers. This method of synthesis is well suited for the modelling of stiff objects containing a relatively few number of modes, and for materials such as wood, metal and glass.

In addition to the basic BWG parameters, two global parameters, Damping and Detune, control the overall decay of modes and their fine spectral positioning, respectively.

There are two playable mechanisms in the BWG module. The first one is an external excitation - usually a pulse or a residual, fed to the system in a feed-forward loop. Alternatively, a sustained internal excitation model named the *bow*, feeds into the system which in turn feeds back into the bowing model, thus creating a closed loop of exciter-resonator. These two mechanisms are working selectively so that when one is active, the other deactivated.

Parameters of the banded waveguide system are summarised in Table 1. The modes of several percussion instruments were extracted by spectral peak picking in MATLAB and stored as as multiples of a given fundamental frequency in an external C++ header file for when the compiler is called.

In order to control the three sets of the BWG, i.e. the direct gains ($dg_1, ..., dg_N$), feedback gains ($fg_1, ..., fg_N$) and partials' fine tuning ($pm_1, ..., pm_N$), a system of polynomial cubic splines based on Taylor coefficients vector is utilised. Therefore, each set is controllable by only 4 parameters, adjustable by the user as a global modal control.

2.2.1 Bowing Model

The bowing model can be best described as a generic nonlinear friction model between a bow and a string using the digital waveguide method. The main control parameters include an `ADSR` which relates to the velocity of the bowing and is activated by a gate allowing the model to

Number of modes	N
Fundamental Frequency	F_0
Direct Gains	$dg_0; dg_1; ... ; dg_N$
Feedback Gains	$fg_0; fg_1; ... ; fg_N$
Partials Modes (fine tuning)	$pm_0; pm_1; ... ; pm_N$
Damping	$damping$
Detune	$detune$
Bow/Exciter Gate	$select$

Table 1. Parameters of the Banded Waveguide Model

produce an internal excitation signal, and `BowPressure` which acts as the force between the bow and the object. Details of the bowing model can be found in [17], [26], [27] and [22]. The model has been implemented in several virtual instruments of the STK, such as the Tibetan Bowl and the Tuned Bar and allows the BWG system to internally excite itself by activating a gate. By adding this element to our module, we offer to the user a new type of control over the instrument: a continuous/sustained excitation on top of the basic BWG structure.

2.3 The 2D Digital Waveguide Mesh Module

The second resonator system (after the banded waveguide model) is a square plate modelled as a 2-dimensional waveguide mesh [15]. The mesh implemented in this project has 8x8 junctions and is parameterised at its terminations (edges) by nonlinear allpass (NLAP) filters (explained in the following section) and lowpass filters as described in [28]. The resonant lowpass filters with cutoff frequency F_c, Q factor Q and Gain G, adjust the decay time of the resonating plate by absorbing high frequency energies faster than low ones over time. NLAP parameters are the reflection coefficients $(-\pi, \pi)$ determined by the users choice of $Gain$ and $FineGain$, as well as the NLAP order which is fixed to 4. Realistic impact sounds ranging from stiff metallic and wooden plates to membranes can be achieved. The plate is excited by the same signal exciting the banded waveguide system (section 2.6).

2.4 Nonlinearity

Most musical instruments have a certain number of nonlinear behaviours which are mainly translated by a dynamic enrichment of the sound's spectrum. The importance of non-linearity varies from one instrument to another. For struck string instruments and percussions, the non-linear compression generated during the hit gives rise to a dynamic displacement of energy between the different resonant modes over time [27]. As a result, sounds become brighter with natural characteristics. When a cymbal, Chinese gong or tam-tam are struck, partials from the high end of the spectrum are intensified relative to those of the low end, i.e. the energy is transferred from low to high frequencies [29]. As described in [28], all-pass filters successfully attempt to provide a source of evolving spectra to the synthesis model to replicate nonlinear coupling between resonant modes, which is often found in highly resonant instruments such as cymbals and gongs.

Function `allpassnn` in the Faust Filter library implements the NLAP filter, which can be found in the mesh and at the end of the banded waveguide system. Function `nonLinearModulator` from the Intrument library provides four types of nonlinear modulation [27].

2.5 Coupling

The coupling parameter allows a transfer of energy from one resonator the another. Our model allows for the two resonators to be played individually, in parallel or coupled together, providing five connection cases to the user:

- BWG only
- DWG only
- BWG and DWG together in parallel
- BWG coupled to DWG
- DWG coupled to BWG

In the coupling cases, the excitation enters only a single model which transmits its output to the second resonator by a factor of $coup < 1$, controlling the coupling intensity. When the two resonators work in parallel without any coupling it is possible for the resonators to sound slightly dissociated. The coupling however binds the two resonators together for a more integrated sound. By tuning parameters appropriately, interesting impact sounds of objects attached to a body can be achieved, as well as using a strongly resonating plate as a plate reverb.

2.6 Excitation

An excitation signal, selected from an excitation bank (parametric or residual) is fed into the system to generate impact sounds of different complexity and timbre. The parametric impulse model is a simple cosine impulse function, where the pulse duration and amplitude are controllable [30]. Several impact residuals, extracted by inverse filtering [31], allow for modal presets to be paired with their residuals in order to improve the realism of the chosen preset, or to be paired with other instrument residuals for hybrid combinations.

3. PHYSICAL AND GRAPHICAL USER INTERFACE

3.1 Hardware

The Sensel Morph is a hardware touch controller, with advanced touch technology in the form of Sensel's Pressure Grid [14].

The Morph is a lightweight and relatively compact interface, with a black surface made from PET plastic. Physical considerations and haptic feedback are particularly important for percussive instruments as they can drastically influence playability and expressivity. As a result, we utilise the 'Developers Overlay' provided by Sensel, which is made of silicone rubber with a smooth silicone top-coating and lays on top of the black surface. This produces an adequate bounce for percussive inputs and allows for smoother aftertouch with the developed physical models.

As Sensel's API and sensor array design allows for complete customisation of its borders, we segmented approximately a third of the sensor (78mm) into a control section. This was done to allow for manipulation and modulation of the model separately from the instrument itself, and to make full use of the users gestural dexterity. To further imitate the properties of vibrating structures and propagation of sound waves we used a centre point in the instrument section, meaning that changes from the X,Y position spread spherically and identically in all directions.

The grid technology leverages a high resolution sensor array and efficient drive scheme to capture rich force images at adaptive scan rates from 250-1000Hz. This allows for tracking of multidimensional and multi-touch input with over 30,000 levels of dynamic range. The abundance of highly efficient and accurate input data in combination, provide a powerful platform for developers to use.

Relevant input analysis data include 1-16 contact point, orthogonal coordinate system and area size: 0-33360 square mm.

3.2 Control Surface and Graphical User Interface

Due to the considerable amount of parametric control available over physical models, an important design consideration is how to group, present and separate these parameters in order to achieve an intuitive control mechanism to the user for immediate and powerful control of the model. This was achieved by separating different sections of the physical model and providing a distinct control section for the interaction between them (see Figure 1):

- Resonator A: Banded Waveguide Model
- Resonator B: The 2D Mesh
- Link: Coupling and level control between the resonators
- Excitation: Bowing, pulse and residuals
- Effects: Delay and reverb controls
- Presets: 7x7 bank with save system
- Master: Volume control and ON/OFF

Not all important details could be displayed to the user in the physical interface, such as the presets, fundamental frequency, individual partial decays, excitation type and coupling values. Therefore, a GUI was created in Pd with the same layout as the control surface but with additional details and information, such as fundamental frequency, individual partial decays, excitation type and coupling values.

3.2.1 Communication

Two Arduino Mega 2560 were used to connect the hardware and audio engine, transferring serial communication to the computer running the audio engine. The first Arduino, running the Sensel's Arduino API, was used to retrieve and send the Morph's sensor-array input data to Pd at a frame rate of 125 Hz. The second Arduino was used to retrieve information from Pd and allows to control parameters from the hardware control surface. This was done with a Pd data stream abstraction `arduino2pd` [32], [33].

4. MAPPING

The system allows for an extensive variety of mapping schemes to be implemented, particularly if multiple contacts and other more complex input data are further investigated. In order to showcase this, we developed a novel mapping scheme inspired by the real physics and interaction of a drum, with some extensions made to it (e.g. bowing).

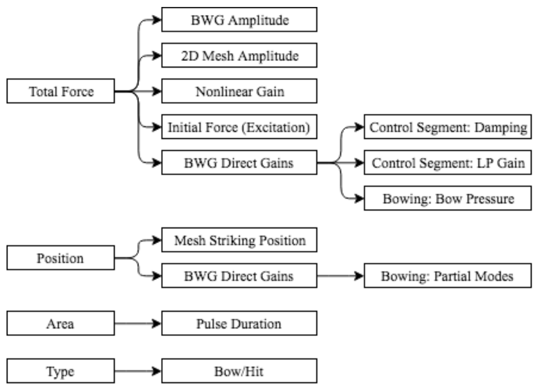

Figure 5. Mapping Scheme

As can be seen in the mapping scheme in Figure 5, the majority of parametric manipulation is performed via force input. This is done to simulate the physical aspects of striking an object. Parameters such as the banded waveguide amplitude and direct gains simply correlate directly to the physical relationship between force and amplitude. Other mappings such as the nonlinear gain are a little more complex and aim to replicate nonlinear characteristics, such as an increase in energy of higher frequencies with high striking amplitudes [34]. Perhaps the most interesting of force mappings is the damping and bow pressure. The damping makes use of the control segment of the sensor, which replicates resonance damping when holding down a drum membrane with one hand and striking with the other. It works by altering the magnitude of the feedback gains, which correlate directly with our auditory perception of material. The bowing is interesting because it provides continuous control of the model, and it's mapping to force allows for intuitive amplitude modulation by simply varying the force applied to the sensor.

Another physically inspired mapping is the position at which the sensor is struck, which performs high-pass filtering using the direct gains of the banded waveguide model. It works by reducing the magnitude of the high frequency modes, and is used to recreate the spectral effect of striking a membrane at positions closer to its boundaries.

An important consideration for the control surface was to keep it simple, intuitive and without the clutter often found in complex synthesis instruments. To this end, we utilise a GUI interface that can be used in conjunction with the control surface to display more detailed aspects of the instrument - such as a graphical view of the modal system, control value ranges, preset names and a spectral analyser of the output.

5. EVALUATION

The evaluation of the instrument consisted of three parts: an instrument function test, an informal interview and a system usability rating. All three parts took place at a lab on campus and lasted approximately 40 minutes for each participant. The test design was primarily based on evaluation methods for digital music instruments (DMI) described in [35]. The test was performed on a Mac Pro with an average measured latency of 44 ms - slightly above the maximum perception of latency for percussive performance of 10 ms.

Participants As a relatively complicated instrument for the inexperienced, we required participants to have at least a moderate experience and knowledge of music technology in order to understand questions asked during the experiment. Experience with performing percussive instruments was desired, but not a requirement. Four participants (23-32 years old) were recruited through purposive sampling to ensure that they fit the target group. All participants had at least 5 years experience with a musical instrument although none specialised in percussion. Overall, levels of knowledge on music technology and/or sound synthesis were high, with a total average of 6.5 years.

5.1 Function Test

The function test was designed to evaluate the instruments usability as a musical instrument. First participants were given two minutes without instruction to explore the instrument. Afterwards, a preset with a short decay was applied and the participant was asked to perform eighth-notes in time with a metronome set at 120 BPM for one minute. The results were recorded into a stereo file with the metronome on the right channel, and audio output on the left. This allowed us to measure average fluctuations in tempo and the ability of participants to perform in time with the metronome. The results of this test were however influenced by imperfections in the instrument, such as occasional missing hits and pressure sensitivity, and also, for some participants, lack of training in percussive playing and time keeping.

5.2 Informal Interview

The informal interview was split into two conditions, one with a focus on performance, and the other on sound design. Both conditions contained two separate sections, one based on 'enjoyment' with qualitative results, and the other on 'playability' with quantitative results. This follows evaluation goals for the performer/user of the DMI [35]. The conditions were conducted randomly so that two of the users begin with the performance, and the others with the sound design. The following section will summarise the qualitative feedback - the quantitative results can be found in Table 2.

The overall response from test participants was positive. All participants commented positively on certain aspects of the instrument. These include: the control surface for it's intuitive layout and integration with the physical model, the bowing model for its unique interaction and sonic capabilities, and the coupling between the two resonators for interesting potential in sound design. Common negative opinions included: Minor delay between playing the pad and hearing the output was noticeable, and made it difficult to play along with the metronome. Hits were occasionally not recognised by the system, which reduced its playing capabilities. Too much force was required to reach the highest amplitudes, and the overall feel of the Morph/overlay could be better.

All participants felt they would utilise the instrument in music production settings, if the negative aspects mentioned were fixed. They would also like to explore more novel and gesturally interesting mapping schemes.

Table 2. Test Results for the performance and sound design. Participants were asked to rate the questions on a scale from 1 (strongly disagree) to 10 (strongly agree).

Performance Playability	**Mean**
The sensor is highly playable	6.8
The instrument is sensitive to input	4.4
The mapping scheme is intuitive	7.3
Interaction with the sensor is pleasurable	5.6
Latency of the system does not affect playability	7.5
Sound Design Playability	**Mean**
The interface design is intuitive	6.8
Creating desired sounds is straightforward	5.8
The instrument is versatile	7.7
The audio synthesis is of high quality	8.4
The mapping scheme is expressive	7.3

5.3 System Usability Scale

A seven-point adjective-anchored Likert system usability scale (SUS) questionnaire was used to determine the overall success of the system [36]. Scores ranged from 69 - 75.5 with an average of 72.4, which equates to adjective ratings between 'Good' and 'Excellent'. Based on previous SUS research, a rating higher than 68 is considered above average for a system usability test.

Unsurprisingly, the participant with the most combined experience of musicianship and music technology scored the highest, showing that overall ratings would perhaps improve with increased understanding of the instrument.

6. DISCUSSION AND FUTURE WORK

In this work we have implemented a digital percussion instrument that allows a performer expressive control over a range of physical model parameters. Comparing our instrument to other products [1–5] the implementation includes both multi-touch and the possibility to continuously press and morph the sound while playing. Furthermore, the modular system allows the player to choose between different excitations and resonators, as well as coupling. Both bowing model and coupling between resonators were aspects positively noted by test participants who also rated the quality of the synthesis as well as the versatility of the instrument highly. In this sense, the advantages of a physical model based instrument over using samples are evident. A downside, however, is the computational power required for real-time use. The latency during testing also resulted in some negative comments by test participants.

Physical modelling provides a great deal of parametric control. Although the test participants did not express that the amount and depth of control available to them was a hindrance, other players less familiar with audio synthesis might. A simpler but more powerful control system might be possible with a structured and effective way of grouping some of these parameters together. For example, identifying the exact ranges of the *feedback gains* that alter our auditory perception of material would allow for a singular control to make a sound more 'wooden' or 'metallic'. The current control system requires knowledge of the banded waveguide system if a player should be able to do this intuitively.

There are many possibilities for extending this instrument further and utilising the capabilities of the sensor with parametric control of a physical model. One clear way to extend the expressive qualities of the instrument would be to utilise sensor input data in more complex ways. An example of this would be to map contact points differently based on the number of contact points and/or the value of an individual contact point. This would allow for different mappings and processing to be performed for a wider variety of gestures, e.g. controlling post-effects with two-fingers or damping with input area size. Ideally, a set of expressive percussive gestures would be defined and then recognised by the sensor, so as to improve the relationship between gestures that percussionists are already accustomed to but with a new digital interface. The control section of the pad could also be further extend to provide tactile control of the control elements of the physical model - this would provide a more fluid experience and reduce the need to change parameters on the control surface.

The Sensel Morph itself is versatile enough to create an entirely new instrument by simply splitting it into additional sections or altering the mapping scheme. An example would be to create a custom overlay which splits the top half of the Morph into a sequencer. However, alternatives to the morph could also be explored as there are sensors that may be more suited towards a percussive interface. This is supported by participants' feedback on not enjoying the texture of the pad itself.

Many other features of the instrument could be altered or have additions made to them, a few of which have been described in this section. The difficulty remains in how to do this in an efficient and effective way that improves user-accessibility, control and expressivity.

7. CONCLUSION

We have describes the design, implementation, and user-testing of a digital percussion instrument with expressive control. Our instrument uses Sensel's Morph as an interface alongside a custom-built control surface for handling an audio engine based on physical modelling. A mapping scheme was implemented to test expressive capabilities of the instrument and extensions made to the audio engine.

User-testing found the instrument to provide an intuitive control over the model parameters although further improvements could be done to the mapping scheme in terms of sensitivity. The combination of different excitation models and resonator couplings make the instrument promising for expressive explorations. However, a high CPU computer is required to run the patch and sensor efficiently enough to be accurately performed in real-time.

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