Design and Evaluation of a Digital Theatre Wind Machine

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ABSTRACT
This paper presents the next stage of an investigation into the potential of historical theatre sound effects as a resource for Sonic Interaction Design (SID). An acoustic theatre wind machine was constructed, and a digital physical modelling-based version of this specific machine was programmed using the Sound Designer's Toolkit (SDT) in Max/MSP. The acoustic wind machine was fitted with 3D printed gearing to mechanically drive an optical encoder and control the digital synthesis engine in real time. The design of this system was informed by an initial comparison between the acoustic wind machine and the first iteration of its digital counterpart [8]. To explore the main acoustic parameters and the sonic range of the acoustic and digital wind machines in operation, three simple and distinct rotational gestures were performed, with the resulting sounds recorded simultaneously, facilitating an analysis of the real-time performance of both sources. The results are reported, with an outline of future work.

Author Keywords
Sonic Interaction Design, physical modeling synthesis, real-time performance, acoustic analysis, historical sound effects, Max/MSP, 3D printing

ACM Classification
[500] Applied Computing – Sound and Music Computing
[300] Human Centred Computing – User Interface Design

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1. INTRODUCTION
Theatre has a long history of the design and live performance of sound with mechanical devices and acoustic materials. This area is therefore a potentially rich resource for Sonic Interaction Design (SID), which researches tactile, multisensory and performative aspects of sonic experience with the aim of designing new sonic interactions [4]. This paper presents the next stage of an investigation into a theatre wind machine, a device first used in the nineteenth century [12]. A wind machine consists of a wooden slatted cylinder and axle mounted on a frame and rotated with a crank handle. The cylinder rotates against an encompassing cloth, and the friction between the slats and cloth creates a wind-like sound. The wind machine was chosen for closer investigation as it makes it possible to explore a continuous action-sound coupling [5] in an experimental setting.

Serafin and de Götzen [13] have already undertaken relevant research in this area focused on Luigi Russolo's *intonarumori* family of mechanical noise intoners created for early twentieth century Futurist musical performances. An analysis of the sound production of these devices informed the creation of a user interface controlling a digital synthesis engine, replicating the original enactive workings of the historical devices. This research aims to extend this method to the area of historical theatre sound effects, and replicate a historical acoustic device as a digital synthesis engine and user interface. It is proposed that this replication will facilitate a fuller examination of the action-sound coupling in an experimental setting.

The wind machine is a simple single-gesture acoustic interface, but it affords the user rich multisensory feedback in the performance of a complex and continuous sound. It is proposed that through an examination of the subtleties that create this experience (sensation of weight and inertia, effort, continuously varying sound, etc.) new strategies can be devised for closing the space between the perceived complexity of the multisensory feedback afforded by the acoustic wind machine and simple digital interfaces affording the same rotational gesture [9]. This process begins by fitting the acoustic wind machine itself with a sensor and using it as the initial performance interface for the digital synthesis engine to ensure that performance of the digital sound reproduces as closely as possible the richness of performance of the acoustic sound. This work will then inform the creation of another interface offering less complex tactile feedback while controlling the digital sound, allowing comparisons to be made between the experiences of performing the same sound with different levels of tactile feedback in an experimental setting. It is proposed that this research has the potential to inform the design of other interfaces affording simple gestures but reliable action-sound couplings for the real-time performance of complex digital sounds.

1.1 Initial System Design and First Analysis
An acoustic wind machine was first constructed according to historical design instructions [7], making a specific example available to model in software. An evaluation of this acoustic device deconstructed the mechanical process behind its stages of sound production using an entity-action model [3], and this formed the basis for the creation of a synthesis engine in Max/MSP[1] using the Sound Designer's Toolkit (SDT)[2] suite of objects [11]. Twelve instances of the most recent iterations of the SDT's dynamic friction model [2], using the *sdt.scraping~*, *sdt.friction~*, *sdt.inertial~* and *sdt.modal~* objects, were used to model each slat in rotation, combining a simulation of a probe sliding on a surface with a nonlinear friction model between

[1] http://www.cycling74.com/
[2] http://soundobject.org/SDT/

one inertial and one modal object. The acoustic wind machine was fitted with an Inertial Measurement Unit (IMU) sensor and a wireless system was implemented with an Arduino and XBee to transfer real-time acceleration and velocity data from its rotation about its central axle to the computer. This first iteration of the digital synthesis engine, and its control by the IMU sensor, was compared to the sonic response of the acoustic machine [8], revealing that further calibration of the friction model was required to produce a frequency response more closely resembling the acoustic wind. Similarly, the digital synthesis engine did not respond as expected to variability in the speed of the rotational gesture. An issue with latency was also highlighted, as there was a perceivable delay between the onset of the acoustic sound and that of the digital sound, pointing to the need to review the efficiency of the Max/MSP patch and flow of data from the IMU sensor.

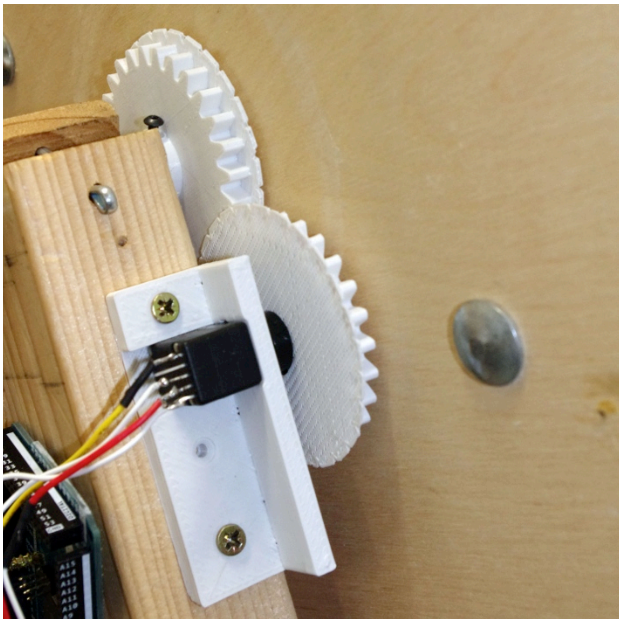

Figure 1: 3D printed gearing coupling the acoustic wind machine's motion to an optical encoder connected to an Arduino.

2. SYSTEM DEVELOPMENT

A discussion of the development and improvement of the digital wind machine system informed by the first acoustical analysis [8] now follows.

2.1 Sensor and Control Data

To translate the rotational movement of the acoustic wind machine into more accurate rotational data, the IMU sensor was abandoned in favour of an optical rotary encoder[3] mechanically coupled to the wind machine's cylinder. Some simple prototype gearing was 3D printed to facilitate this coupling (see Figure 1). As the encoder was mounted to the acoustic wind machine's a-frame stand rather than a moving part of the mechanism, the Arduino reading its movement could be directly connected to the computer via USB, removing the need for a wireless system and increasing the speed of data transfer via the serial bus. Data from the encoder was mapped to a 360° rotation in Max/MSP, representing the trajectory of the point of origin (slat F). Using the degree values of the slat placement on the acoustic wind machine, this data was placed out of phase a further eleven times, creating a separate stream of control data for the position of each of the twelve slats (see Figure 2). The velocity and acceleration of the encoder were also calculated to inform further parameters to the sound model.

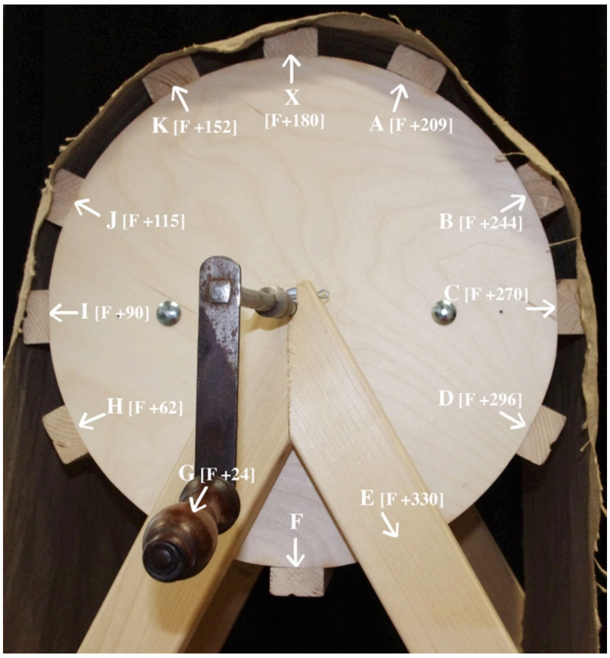

Figure 2: Side view of the acoustic wind machine, showing slat positions in a 360° rotation from their position of origin (slat F).

The mapping strategy focused on creating complexity from the encoder's smooth data stream in order to reflect the gesture afforded by the acoustic wind machine. This clockwise rotational gesture is far from smooth, and is in fact comprised of two distinct parts due to the influence of gravitational force and the way the cloth has been fixed to the machine, i.e. one side hangs freely while one side is coupled to the acoustic wind machine's a-frame (Figure 3). The first half of the rotation (from bottom to top) requires much more effort on the part of the performer and generally produces a signal with higher amplitude, while the second half (from top to bottom) requires a less forceful movement. This gestural shape creates a variable envelope in the resulting acoustic sound:

1. The first half of the rotational gesture produces a sound with slightly higher amplitude, while the second half of the gesture produces a sound with lower amplitude.
2. A slower rotational speed produces a sound of lower overall amplitude.
3. A faster rotational speed produces a sound of higher overall amplitude.
4. Variations in the overall speed of rotation will produce a corresponding variation in overall amplitude.
5. At higher and increasing speeds, the friction between the slats and cloth creates a characteristic 'whistling' sound (an audible pitch) that ascends during the first part of the gesture and descends during the second half of the gesture.

[3] The optical encoder used was Bourns type ENA1J-B28-L00128L.

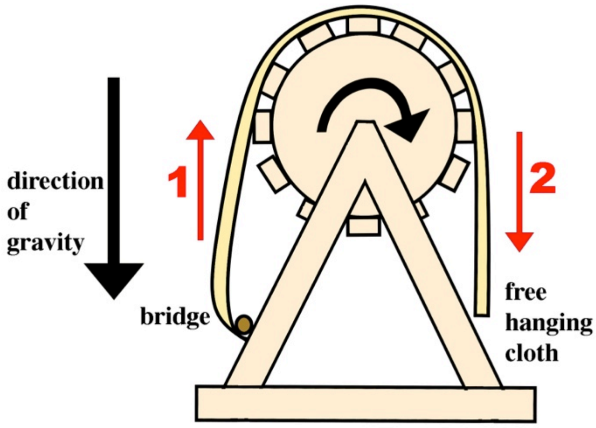

Figure 3: Diagram of the two-part rotational gesture afforded by the acoustic wind machine in a clockwise motion, and the difference in the cloth tension on each side.

To recreate this behavior in the digital domain, the control data for each slat position was first converted to signal rate, and then passed through an inertia model created with a 10ms delay and logarithmic filtering using *slide~*.[4] This data then passed through to the velocity parameter of each *sdt.scraping~* (Table 1), forming the trajectory of the 'scrape' for each slat. To add further variation to the resulting sound, the grain parameter to *sdt.scraping~* was subtly modulated according to the position of each digital slat during rotation, with the values rising during the first half of the rotational gesture and falling during the second half, reflecting the angle of the slat in relation to the encompassing cloth. Acceleration data from the encoder was used to modulate the force parameter to *sdt.scraping,* increasing the force as the rotation accelerated. The overall amplitude envelope of the digital synthesis engine was controlled with velocity data from the encoder's rotation, ensuring lower amplitudes at slower speeds. Changes in the encoder's data stream were monitored in real time, allowing a *line~* object to be triggered to stop and start the overall sound appropriately in time with the movement of the crank handle on the acoustic wind machine.

2.2 Sound Model

Parameters to the digital slat model were re-calibrated following the initial evaluation of the digital synthesis engine [8]. The revised settings are outlined in the tables below. These parameters were chosen to produce a sound that reflected the roughness of the acoustic wind machine sound, which is perceivably 'noisy' in operation, as accurately as possible.

Table 1: Parameters to sdt.scraping~

Surface profile (a signal)	*noise~*
Grain [density of micro-impacts]	*0.080596, modulated by encoder data*
Velocity (m/s)	*Real-time optical encoder data*
Force (N)	*0.546537, modulated by encoder data*

[4] The inertia model was developed from code by jvkr on the Cycling '74 forum (https://cycling74.com/forums/topic/line-with-inertia/).

Table 2: Parameters to sdt.inertial~

Mass of inertial object (Kg)	*0.01*
Fragment size (to simulate crumpling)	*1*

Table 3: Parameters to sdt.friction~

External rubbing force	*signal from sdt.scraping~*
Bristle stiffness (evolution of mode lock-in)	*500.*
Bristle dissipation (sound bandwidth)	*40.*
Viscosity (speed of timbre evolution and pitch)	*1.2037*
Amount of sliding noise (perceived surface roughness)	*0.605833*
Dynamic friction coefficient (high values reduce sound bandwidth)	*0.159724*
Static friction coefficient (smoothness of sound attack)	*0.5 (for Hemp cloth and Wood)*
Breakaway coefficient (transients of elasto-plastic state)	*0.174997*
Stribeck velocity (smoothness of sound attacks)	*0.103427*
Pickup index of object 1 (contact point)	*0*
Pickup index of object 2 (contact point)	*0*

Table 4: Parameters to sdt.modal~

Frequency factor	1
Frequency of each mode (Hz)	380, 836, 1710
Decay factor	0.005
Decay of each mode (s)	0.8, 0.45, 0.09
Pickup factor	2.2
Pickup0_1	50
Pickup0_2	100.
Pickup0_3	80.
Fragment size	1
Active modes	3

To reduce strain on the computer's CPU, each digital slat model and its corresponding control signal was implemented within its own *poly~* object, facilitating DSP muting when the slat passed out of range of the cloth. This also allowed for downsampling within *poly~,* which was implemented by a factor of 4, resulting in a much smoother operation of the SDT object configurations and an improved resulting sound. The digital synthesis model was expanded further to include a very simple model of the acoustic wind machine's cloth, which is its main resonator. The *sdt.modal~* object adds modal resonance to the friction model, but the role the cloth plays in dispersing the sound in the acoustic domain should also be taken into account. The friction sound created at each of the seven active slats (Figure 1) propagates through the rough cloth on either side of the central wooden cylinder. The cloth is a dispersive medium, so the speed of wave propagation through it is not the same at all frequencies [14]. In addition, the cloth has a slightly different tension on each side of the cylinder due to the way it is coupled to the a-frame (Figure 3). The tight side of the cloth, which is coupled to a wooden pole 'bridge' pinned to the a-frame, is similar to a bowed string, with the slatted cylinder 'bowing' the cloth during rotation. As such, a bidirectional digital waveguide model usually used to simulate string vibration in Karplus-Strong synthesis [6] was adapted for this work. A digital waveguide in series with a low-pass filter and an all-pass filter was used to simulate dispersion of the friction sound through the tight side of the cloth, allowing for some damping due to its coupling to the acoustic wind machine's 'bridge.' Dispersion through the freely hanging side of the cloth was modeled using the most basic method, without damping, of a delay line in series with an all-pass filter [14].

3. EVALUATION

To evaluate the effectiveness of the new real-time synthesis engine and sensor configuration, three distinct rotational gestures were performed while the acoustic and digital wind machines were simultaneously recorded. This procedure followed that of the initial analysis [8], with simple gestures chosen to give as complete a picture as possible of the of both systems in performance to facilitate their comparison:

1. A single rotation.
2. Five rotations to produce a continuous sound.
3. Ten rotations that start at speed, but then diminish in energy.

These gestures were repeatedly recorded, giving a total of 30 examples for each. Representative audio clips were then chosen for analysis using the MIR Toolbox in Matlab [10].

3.1 Results

3.1.1 Amplitude Envelope

In the following graphs, the acoustic sound is shown in blue and the digital sound is shown in red.

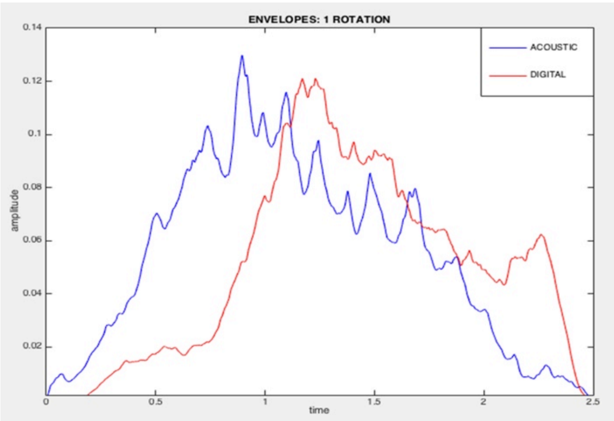

Figure 4: Envelopes for 1 Rotation of the Acoustic and Digital Wind Machines

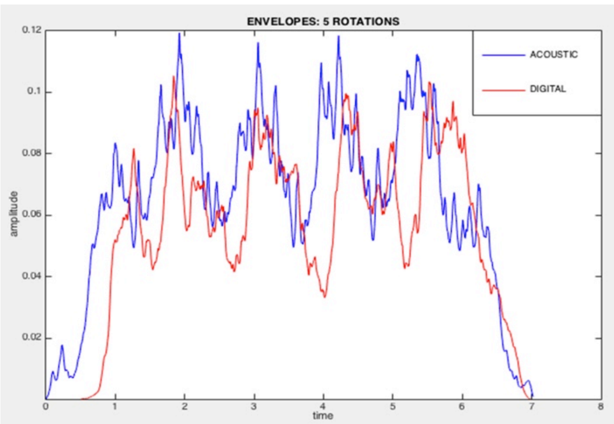

Figure 5: Envelopes for 5 Rotations of the Acoustic and Digital Wind Machines

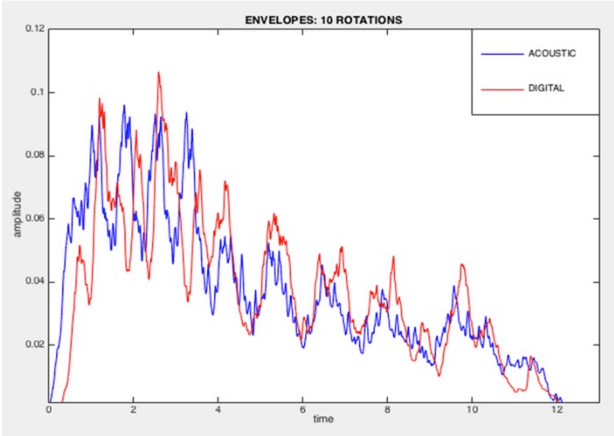

Figure 6: Envelopes for 10 Rotations (diminishing in energy) of the Acoustic and Digital Wind Machines

3.1.2 Spectrum

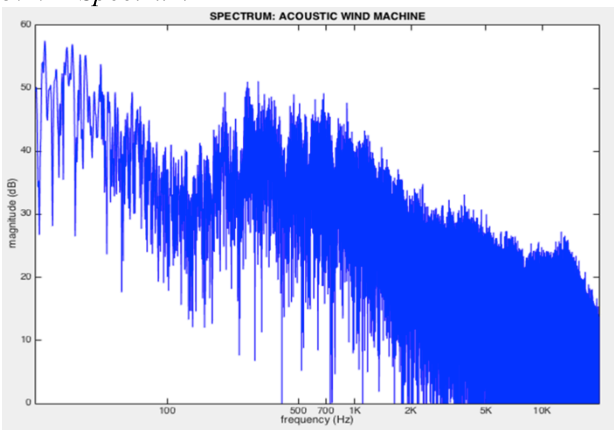

Figure 7: Spectrum of Acoustic Wind Machine

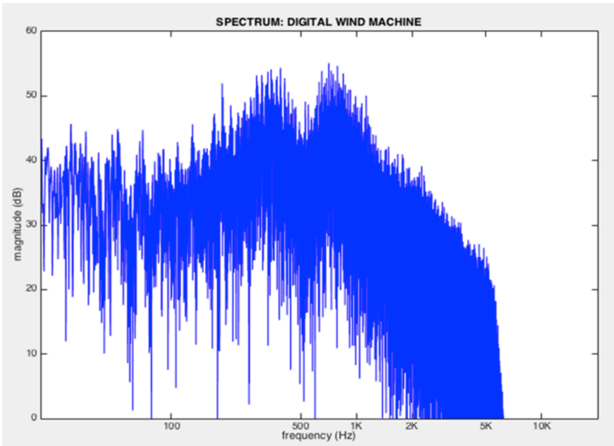

Figure 8: Spectrum of Digital Wind Machine

4. DISCUSSION

The response of the new digital synthesis engine has greatly improved upon that of the initial system [8]. The previous latency issue has been almost eliminated, and the digital wind sound begins and ends appropriately. This is due to the tight mechanical coupling between the optical encoder and the acoustic wind machine, the increased speed of data transfer and the effective management of CPU implemented in Max/MSP.

Similarly, the amplitude envelope of the digital wind machine has improved. The system is now capable of some variability in performance due to the inertia model giving shape to the rotational control data from the optical encoder, and the modulation of the amplitude of the digital sound according to the velocity of rotation (Figure 6). The progress of the digital sound is now closer to that of its acoustic counterpart, and sounds like the output of a rotating machine when the performance gesture is regular and repetitive. The envelope will require some further calibration to ensure that the inertia model is not overly delaying the progress of the digital wind machine, particularly during repeated rotations (Figure 5).

The spectrum of the digital synthesis engine is now closer to that of the acoustic wind machine. The digital sound is perceivably wind-like, but contains some of the same roughness of the acoustic sound created by the texture of the encompassing cloth. The digital spectrum does lack power at those higher frequencies that are responsible for the acoustic wind machine's characteristic 'whistling,' which varies in pitch according to the speed of rotation. Further real-time modulation of parameters to the SDT objects will be investigated, as well as control over the delay time to the bidirectional cloth model, to brighten the digital sound and create the same characteristic 'whistling.' Pitch control via changes in a digital waveguide's delay time is a method informed by Karplus-Strong synthesis [6].

This work will continue with perceptual testing in an experimental setting with participants. A listening test to compare the acoustic and digital wind sounds, as well as a study of the acoustic wind machine in operation as a sounding object and as a controller for the digital wind machine engine will be undertaken. The results of these experiments will inform further calibration of the digital system parameters, as well as the design of a crank controller with less tactile feedback to facilitate a purely digital performance, enabling an investigation into the perceived complexity of the acoustic wind machine in operation compared with a simpler digital interface affording the same rotational gesture [9]. The potential of a simple gesture of rotation to control a complex synthesis system will be further explored through the application of the digital wind machine's mapping model to the performance of other digital sounds.

5. CONCLUSION

The current development of the design of a digital model of a theatre wind machine has been described, in addition to its comparison with the acoustic version on which it is based. Future work in this area, including perceptual testing of the system, was also outlined.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] Avanzini, F., Serafin, S. and Rocchesso, D., Modeling interactions between rubbed dry surfaces using an elasto-plastic friction model. in *International Conference on Digital Audio Effects* (DAFX) (Hamburg, Germany, 2002).

[2] Delle Monache, S., Drioli, D.D.C., Fontana, F., Papetti, S., Polotti, P. and Rocchesso, D. Closing the loop of sound evaluation and design (CLOSED): Deliverable 2.1, algorithms for ecologically-founded sound synthesis: Library and documentation, Technical report, UNIVERONA (Verona), 2007.

[3] Farnell, A. *Designing Sound*. MIT Press Cambridge, 2010.

[4] Franinović, K. and Serafin, S. *Sonic Interaction Design*. MIT Press, 2013.

[5] Jensenius, A.R. *Action-sound: Developing Methods and Tools to Study Music-Related Body Movement.* PhD thesis, Department of Musicology, University of Oslo. 2007.

[6] Karjalainen, M., Välimäki, V. and Tolonen, T. Plucked-string models: From the Karplus-Strong algorithm to digital waveguides and beyond. *Computer Music Journal*, *22* (3). 17-32.

[7] Keenan, F. A Theatre Wind Machine as Interactive Sounding Object *International Conference on Live Interfaces (ICLI) Doctoral Colloquium* (University of Sussex, Brighton, UK, 2016).

[8] Keenan, F. and Pauletto, S. An Acoustic Wind Machine and its Digital Counterpart: Initial Audio Analysis and Comparison *Interactive Audio Systems Symposium (IASS)* (University of York, York, UK, 2016).

[9] Keenan, F. and Pauletto, S. "'Listening Back': Exploring the Sonic Interactions at the Heart of Historical Sound Effects Performance," *The New Soundtrack,* vol. 7, pp. 15-30, 2017.

[10] Lartillot, O. and Toiviainen, P., A Matlab toolbox for musical feature extraction from audio. in *International Conference on Digital Audio Effects* (DAFX) (Bordeaux, France, 2007), 237-244.

[11] Monache, S.D., Polotti, P. and Rocchesso, D., A Toolkit for Explorations in Sonic Interaction Design. in *Proceedings of the 5th Audio Mostly Conference: A Conference on Interaction with Sound*, (Piteå, Sweden 2010), 1.

[12] Moynet, J., Jackson, A.S. and Wilson, M.G. *French Theatrical Production in the Nineteenth Century: "L'Envers du Théatre" by M.J. Moynet, 1873*. Max Reinhardt Foundation with the Center for Modern Theatre Research, State University of New York, USA, 1976.

[13] Serafin, S. and De Götzen, A. An Enactive Approach to the Preservation of Musical Instruments Reconstructing Russolo's Intonarumori. *Journal of New Music Research*, *38* (3). 231-239.

[14] Smith, J.O. *Physical audio signal processing: For virtual musical instruments and audio effects*. W3K Publishing, 2010. https://ccrma.stanford.edu/~jos/pasp/