Intuitive Control of Rolling Sound Synthesis

Simon Conan, Mitsuko Aramaki, Richard Kronland-Martinet, and Sølvi Ystad

Laboratoire de Mécanique et d'Acoustique (LMA), CNRS UPR 7051,
Aix-Marseille Université, Centrale Marseille,
31 Chemin Joseph Aiguier, 13402 Marseille Cedex 20, France
{conan,aramaki,kronland,ystad}@lma.cnrs-mrs.fr

Abstract. This paper presents a rolling sound synthesis model which can be intuitively controlled. For that purpose, different aspects of the rolling phenomenon are explored: physical modeling, perceptual studies and signal morphology. Based on these approaches, we propose a synthesis model that reproduces the main perceptual features responsible for the evocation of rolling action. Finally, a control strategy based on ball's properties (perceived size, asymmetry, speed, trajectory) and the irregularity of the surface is proposed.

Keywords: Rolling Sounds, Sound Synthesis and Control, Environmental Sound Synthesis, Sound Invariants, Physically Informed Synthesis, Rolling ball.

1 Introduction

This study is part of a larger project (*MétaSon*[1]) which aim is to build a realtime sound synthesis platform that offers intuitive controls of sounds to end users. In fact nowadays almost any everyday sound can be realistically synthesized, but the question of intuitive control of sound synthesis processes is still a substantial challenge. For instance, an impact sound can be represented and synthesized by a sum of exponentially decayed sinusoids [38]. However, obtaining a specific impact sound reflecting for instance the material, size or shape of the impacted object by acting directly on the synthesis parameters (amplitudes, frequencies and damping coefficients of the sinusoidal components) is quite impossible, even for expert users. To cope with this problem, perceptually relevant signal structures have to be identified through listening tests to define mapping strategies that enable such intuitive controls.

One aim of the *MétaSon* project is to propose a sound synthesizer with associated high-level (or intuitive) controls. To achieve this, we assume that the sound (signal) contains so-called sound *invariants*, *i.e.* signal morphologies that are responsible for the recognition of particular sound events [15,27]. These *invariants* can be either *structural invariants* or *transformational invariants*. *Structural invariants* reflect the intrinsic properties of an object and enable us to recognize it, whereas *transformational invariants* are linked to external interactions with

---

[1] `http://metason.cnrs-mrs.fr/`

M. Aramaki et al. (Eds.): CMMR 2012, LNCS 7900, pp. 99–109, 2013.

this object and enable us to recognize the actions that produced the sound. For instance a string produces a sound with a particular spectro-temporal structure that is recognized by the listener, even if it is bowed (violin), plucked (guitar) or hit (piano). Likewise, it is possible to recognize that a cylinder bounces even if it is made of glass, wood or metal [25]. Hence, "if an event is something happening to a thing, the *something happening* is presumed to be specified by *transformational invariants* while the *thing* that it is happening to is presumed to be described by *structural invariants*" [28].

For instance, Warren and Verbrugge studied auditory *transformational invariants* with recorded bouncing and breaking glass sounds [39]. They first showed listeners' ability to differentiate these sounds, then they identified the specific patterns responsible for the recognition of the interaction and then validated the identified *transformational invariants* by synthesis. Concerning the object, listening tests revealed that the evocation of a specific material is correlated to the damping of spectral components [37,21,16] and to the roughness [2], while the hardness of the striking mallet is related to the characteristics of the time attack [13]. Aramaki *et al.* used the results of such studies to propose an impact sound synthesizer with high-level controls [3] that enables the user to directly control perceived attributes of sound sources such as the object's material or size. These previous studies confirm that these *invariants* are strong enough to evoke both the object an the interaction with this object.

On the basis of these *structural* and *transformational invariants*, we propose a sound synthesis *action/object* paradigm in which the sound is defined as the result of an action on an object. In this paradigm, the object's properties are separated from the interactions it is subjected to. From a synthesis point of view, we used subtractive synthesis models based on a source-filter structure. This kind of model originally came from speech analysis and synthesis [4], but has also been studied in the context of musical sounds [31] and in the context of continuous interaction sound synthesis [38,22]. The source-filter model is an approximation of physical modeling : it stands that in an interaction, the physical exciter (for instance the vocal folds in the case of speech production) is decoupled from the resonator (the vocal tract). In the case of voiced vowel synthesis, the excitation (source) is a pulse train which is passed through a filter bank that simulates the vocal tract resonance for a particular vowel. In the case of rubbing sounds for instance, the interaction (source) can be represented by an adequate excitation signal while the object's modes (filter) can be represented by an adequate resonant filter bank [14].

This paper is devoted to a particular type of interaction, the rolling action. In the next section we will present the literature on rolling sounds, then in the 3 we will propose a sound synthesis model for rolling sounds. Section 4 will be devoted to the control strategy, and in the last section we will conclude and propose some perspectives for this work.

2 Previous Studies on Rolling Sounds

Different approaches to the synthesis of rolling sounds can be found in the literature. Physical modeling of the phenomenon and the computation of equations with finite difference scheme has been proposed. Stoelinga et al. derived a physical model that produces rolling sounds [32] from previous studies on impact sounds on damped plates [10,23]. This model can reproduce phenomena like the Doppler effect, which is also found in the measures. However, sound examples are not fully convincing, i.e. the sounds do not clearly evoke rolling objects. This can be explained by the lack of amplitude modulation, as the model considers the rolling object as a perfect sphere (i.e. the mass center is the geometrical center), which is never the case in reality. It is important to note that these models cannot be computed in real time.

Another approach is the physically informed modeling. In [17], Hermes proposed a synthesis model that consisted of simulating the excitation by a series of impacts following a Poisson law amplitude modulated to account for the asymmetry of the ball. This pattern was further convolved with the impulse response of the object (represented by a sum of gamma-tones) on which the ball rolled. The author justified the shape of the impulse response by the fact that the collisions between the ball and the plate are "softer" than in a classical representation that uses a sum of exponentially decaying sinusoids. Otherwise, in order to feed the source-filter model with parameters from real recorded sounds, Lagrange et al. [22] and Lee et al. [24] proposed an analysis/synthesis scheme. This scheme consists in extracting the excitation pattern (considered as a series of micro impacts) and the object's resonances (the resonance of the rolling object and the surface on which it rolls are not separated). Van den Doel et al. [38] proposed a model where modal resonators were fed with a noise whose spectral envelope was defined by $\sqrt{1/(\omega-\rho)^2+d^2}$ where ρ and d are respectively the frequency and the damping of the resonance, in order to enhance the resonance near the rolling object's modes. The authors also proposed a similar source-filter model to generate rubbing sounds. In both of these models, the velocity is conveyed by filtering the signal with a lowpass filter whose cutoff frequency is tuned according to the motion's speed. Rath proposed a model for rolling sounds which is between physical modeling and physically informed considerations [30]. Based on a nonlinear contact model for impact sound synthesis [5], Rath added a supplementary physically inspired control layer to produce rolling sounds. More details concerning this model will be given later (Sect. 3.1).

As far as sound "invariants" related to the evocation of rolling objects are concerned, several studies can be found in the literature. For instance, Houben et al. studied the auditory ability to distinguish the largest or the fastest ball between two recorded sounds. They showed that at constant velocity (respectively at constant size) listeners can distinguish the largest (respectively the fastest) rolling ball with good accuracy. The performance is impaired when the two factors (i.e. velocity and size) are crossed [19]. They also attempted to identify acoustic cues that characterize the size and speed of rolling balls, like auditory roughness or spectral structure. The influence of spectral and temporal properties was studied in [20] by crossing the temporal content of a stimulus with the spectral content of another stimulus and using the obtained sound (the obtained stimulus had its spectrum very close to one stimulus and its temporal envelope very close to the other stimulus) in a perceptual experiment. It was shown that only the spectral structure was used to determine the fastest or largest ball and that results were better for the size judgement than for the speed judgement. However only recordings without clear amplitude modulations (due to an unbalanced ball or a deviation from perfect sphericity) were used in the experiment. This can explain why no temporal cues were found. The authors further investigated the influence of this amplitude modulation in [18]. Artificial amplitude modulations were added to the recordings used in the previous experiments. Perceptual experiments showed that amplitude modulations clearly influence the perceived size and speed.

Another important perceptual effect is caused by the influence of the modes of the support on which the ball rolls. These modes are excited differently along the ball's trajectory, depending on the excitation point. This effect can be observed as varying ripples in the time-frequency representation of rolling sounds and is due to the interference between the sound generated at the point of contact between the ball and the plate and the sound reflected at the edges of the plate [33]. Murphy *et al.* [29] performed a series of perceptual experiments to judge the quality of the analysis-synthesis algorithm described in [22]. In a first experiment, the listeners described the rolling sounds as "static". Then they simulated the ball's displacement with a time-varying comb filter, which resulted in rolling sounds that were perceived as more realistic.

Based on those previous studies on synthesis and perception of rolling sounds, we will propose a sound synthesis scheme in the next section.

3 Sound Synthesis Model

The proposed synthesis model aims at reproducing the main perceptual features behind the evocation of rolling actions. For that, we explored different aspects of the rolling phenomenon (physical, perceptual and signal morphology) and we concluded on the relevance of the following attributes: the nonlinear interaction force between the rolling ball and the plate, the amplitude modulation due to the imperfect sphericity of the ball, the timbre variation induced by the displacement of the contact point along the trajectory and the timbre variation induced by the ball's velocity. In the proposed synthesis scheme, each of these attributes are reproduced by separate processes. Hence, we here propose a modular approach to synthesize rolling sounds. Each step of this sound synthesis model will be detailed in this section.

3.1 Nonlinear Interaction Force

From our point of view, the model proposed by Rath [30] produces the most convincing sounds. This model consists in transforming a physical model of colliding objects into a rolling sounds model. Basically, the model proposed by

Avanzini *et al.* [5] allows to produce bouncing sounds. This model couples an exciter (a hammer or a ball for instance) to a resonant object (which is defined by its modes, each of them represented by a mass-spring-damper system) with a nonlinear interaction force that takes into account the compression and the velocity of compression between the two colliding objects [26] as described in the equations below:

$$\begin{cases} x = x_e - x_r \\ \ddot{x}_r + g_r \dot{x}_r + \omega_r x_r = \frac{1}{m_r} f(x, \dot{x}) \\ \ddot{x}_e = -\frac{1}{m_e} f(x, \dot{x}) + g \end{cases} \tag{1}$$

with

$$f(x, \dot{x}) = \begin{cases} kx^\alpha + \lambda x^\alpha \dot{x} & , x > 0 \\ 0 & , x \leq 0 \end{cases} \tag{2}$$

The terms labeled with an r stands for the resonant object and those labeled with an e for the exciter (for further information on the physics or on the implementation, refer to [5,30]). The term x represents the compression between the two objects, and f is the nonlinear interaction force between the exciter and the surface that depends on the compression x. By adding a time-varying signal that captures the fact that a rolling ball "scans" the rough surface on which it rolls in a particular way to the compression term, this model produces sounds that clearly evoke a ball rolling on a rough surface. As one can note in Fig. 1, this interaction force is a series of impacts. Moreover, this force has a particular structure, *i.e.* it evolves over time in a particular way and the impacts are related in a specific manner.

It is possible to synthesize a signal that captures the main characteristics of this nonlinear interaction force (paper in preparation). Indeed, we can simulate

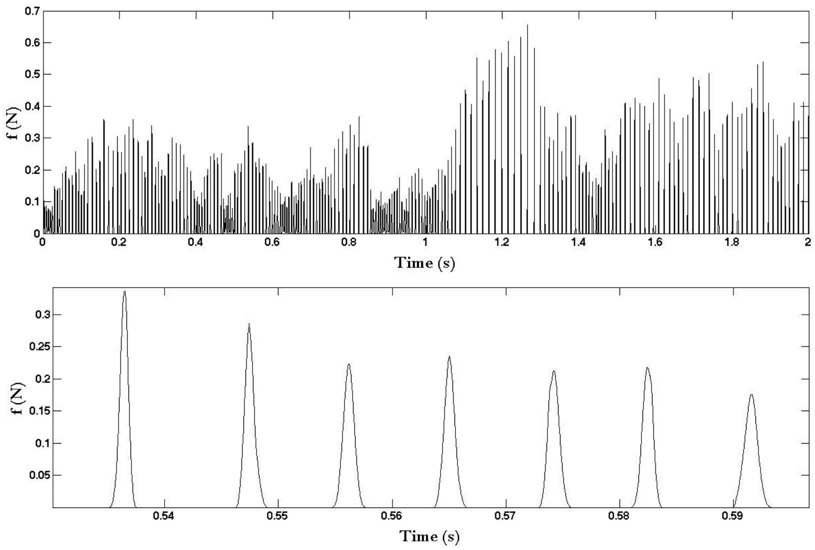

Fig. 1. Interaction force between the ball and the surface resulting from a simulation of the synthesis model proposed by [30] *(top)* and a zoom on this force *(bottom)*

the behavior of the two time series by the amplitudes of the impacts (A^n) and the intervals between each impact (Δ_T^n). Thus, our model allows to reproduce series of Dirac pulses with specific statistics.

Then, each Dirac pulse is shaped by an impact model. A simple and efficient impact model is the raised cosine (see [8]). Moreover, as the interaction force is nonlinear, the impact's duration varies with its amplitude [9,6]. This effect is taken into account. The sharpness of the pulses, which affect the sound's brightness, can also be controlled by empirically using an additional exponent ξ in the original raised cosine model. The used pulse model is then :

$$F_{\mathrm{exc}}(n) = \begin{cases} \frac{F_{\max}}{2^{\xi}} \left[1 - \cos\left(\frac{2\pi n}{N_{\mathrm{exc}}}\right)\right]^{\xi} & , n \in [\![0, N_{\mathrm{exc}}]\!] \\ 0 & , \text{otherwise} \end{cases} \tag{3}$$

with $F_{\max}$ the impact's amplitude and N_{exc} the impact duration.

From a perceptual point of view, we observed that it is the nonlinear interaction force between the rolling ball and the plate that carries the main relevant information that characterizes the action *to roll.* This force can be considered as a transformational invariant related to the rolling action and, in the proposed synthesis paradigm {source/resonance}, as the source signal. Indeed, by convolving the computed force resulting from the interaction of a rolling ball and a rough surface with an impulse response of a resonant object, a realistic rolling sound is produced.

3.2 Amplitude Modulation

As exposed in Sect. 2, Houben showed that modulating the amplitude of rolling sounds influence the perceived size and speed [18]. Such an amplitude modulation can be due to imperfect sphericity of the rolling marble, or to the asymmetry of its mass center. As proposed by multiple authors [17,18,30], the modulation can be approximated by a sinusoidal modulation. Thus, the incoming signal $f(t)$ is modulated as :

$$y(t) = [1 + m\cos(2\pi\nu_m t)]\, f(t) \tag{4}$$

with $\nu_m \propto \dot{x}/r$, $\dot{x}$ and r are respectively the ball's velocity and radius.

3.3 Position Dependent Filtering

As previously pointed out, a marble that rolls on a plate excites its modes differently along its trajectories, depending on its location on the plate. This effect is due to the interference between the sound generated at the point of contact between the ball and the plate and the sound reflected at the edges of the plate [33]. Each reflected source is the delayed version of the sound, and the delay time of each comb filter can be calculated thanks to an image source method [1]. Hence, we simulate the reflection of the four first order images for a square plate, depending on a chosen listening point on the plate, on the ball's position and on the first natural frequency of the plate. As already pointed out by Murphy *et al.* [29], this effect enhance the sensation of the ball's displacement.

3.4 Velocity Dependent Filtering

In the synthesis model for rubbing sounds proposed by Van den Doel *et al.* [38], the transversal velocity of the contact point controls the cutoff frequency of a lowpass filter. This is important for the rendering of the gesture velocity sensation. As we found that using this lowpass filtering step in the rolling sound synthesis model also convey information about velocity of the rolling ball, this effect is added to our rolling model.

The whole synthesis scheme is presented in Fig. 2. The associated controls will be presented in the next section.

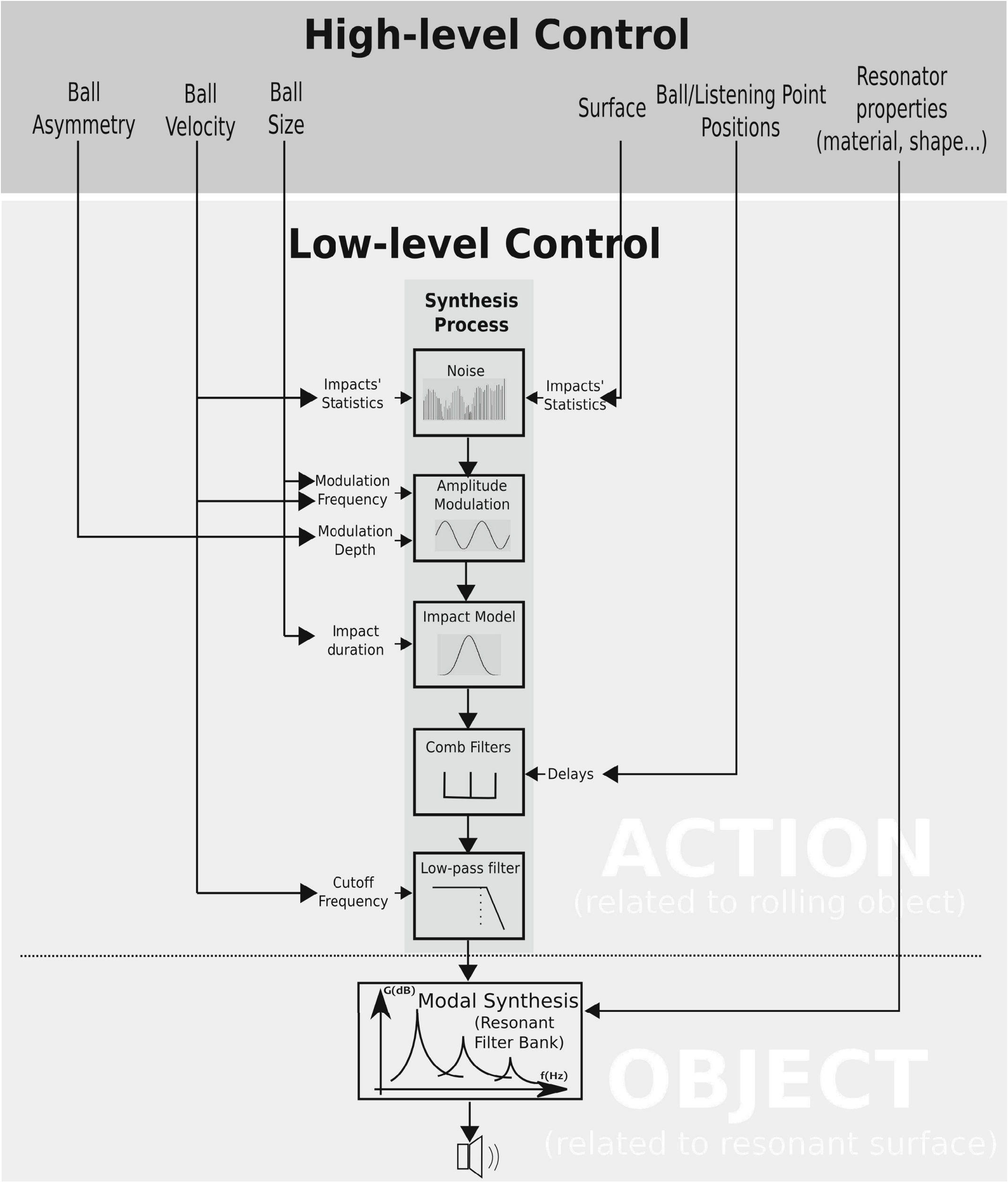

Fig. 2. General framework of the synthesis model to produce rolling sounds. High-level controls associated with the resonant surface were proposed in [3].

4 Control Strategy

Intuitive controls that are adapted to non-expert users are displayed in the upper part of Fig. 2. The proposed controls on the ball's properties are its perceived size, asymmetry, speed and trajectory. The irregularity of the surface can also be controlled. The mapping between high- and low-level controls (*i.e.* synthesis parameters defined in Sect. 3) are also presented in Fig. 2.

As one can note, the action is clearly separated from the resonant object (the surface on which the ball rolls) according to our paradigm. This means that the source part of the model can be modified to evoke interactions, independently of the resonant object. Conversely, it is possible to change the perceived properties of the resonant object while preserving the type of interaction. Concerning the resonant object, high-level controls associated with the perceived material, size or shape were previously proposed [3]. Going further, this distinction between interactions and object should make it possible to propose control strategies facilitating the creation of sound metaphors, like "bouncing water" or "rolling wind".

5 Conclusion

We proposed a rolling sound synthesis model in a source-filter approach. This model is clearly adapted to our paradigm that separates the action and the object in the modeling process.

This model is controllable in an intuitive way and a real-time implementation has been carried out. Thanks to this real-time implementation, parameters like the velocity of the ball can be directly controlled by the user with a graphical tablet as input for more interactivity.

Possible improvements could be achieved with the use of inharmonic comb filters to simulate the ball's position. In fact in [33], Stoelinga *et al.* analyzed the wave dispersion (i.e. the frequency dependent wave velocity) in a plate and concluded that frequency dependent comb filters added more realism when simulating a ball approaching the edge of a plate. This was confirmed thanks to perceptual experiments by Murphy *et al.* [29].

A generic model that allows continuous transitions between interactions (from rolling to scratching or from rubbing to squealing) is currently investigated, in order to propose intuitive navigation through the possible interactions between solids. Actually, the rolling model is sufficiently generic to synthesize various interactions such as rubbing and scratching [11,12], and we are currently investigating the integration of other interactions such as nonlinear friction [7,34].

This synthesizer is a powerful tool, for sound design or sonification, but also for fundamental research, to investigate auditory perception as it was done for instance by Thoret *et al.* who studied the relations between gestures and sounds [35,36]. In particular, the influence of the velocity profile (profiles of a human gesture versus the profiles of a rolling ball for instance) on the perceived interaction could be precisely investigated since the velocity is one of the control parameters of the synthesizer.

Acknowledgements. The authors would like to thank the French National Research Agency (ANR) which supports the *MetaSon* Project - CONTINT 2010: ANR-10-CORD-0003.

References

1. Allen, J., Berkley, D.: Image method for efficiently simulating small-room acoustics. J. Acoust. Soc. Am. 65(4), 943–950 (1978)
2. Aramaki, M., Besson, M., Kronland-Martinet, R., Ystad, S.: Timbre perception of sounds from impacted materials: behavioral, electrophysiological and acoustic approaches. Computer Music Modeling and Retrieval. In: Genesis of Meaning in Sound and Music, pp. 1–17 (2009)
3. Aramaki, M., Gondre, C., Kronland-Martinet, R., Voinier, T., Ystad, S.: Imagine the sounds: An intuitive control of an impact sound synthesizer. In: Ystad, S., Aramaki, M., Kronland-Martinet, R., Jensen, K. (eds.) CMMR/ICAD 2009. LNCS, vol. 5954, pp. 408–421. Springer, Heidelberg (2010)
4. Atal, B., Hanauer, S.: Speech analysis and synthesis by linear prediction of the speech wave. The Journal of the Acoustical Society of America 50(2B), 637–655 (1971)
5. Avanzini, F., Rocchesso, D.: Modeling collision sounds: Non-linear contact force. In: Proceedings of the COST-G6 Conference Digital Audio Effects (DAFx-01), pp. 61–66 (2001)
6. Avanzini, F., Rocchesso, D.: Physical modeling of impacts: theory and experiments on contact time and spectral centroid. In: Proceedings of the Conference on Sound and Music Computing, pp. 287–293 (2004)
7. Avanzini, F., Serafin, S., Rocchesso, D.: Interactive simulation of rigid body interaction with friction-induced sound generation. IEEE Transactions on Speech and Audio Processing 13(5), 1073–1081 (2005)
8. Bilbao, S.: Numerical Sound Synthesis: Finite Difference Schemes and Simulation in Musical Acoustics. John Wiley & Sons (2009)
9. Chaigne, A., Doutaut, V.: Numerical simulations of xylophones. i. time-domain modeling of the vibrating bars. Journal of the Acoustical Society of America 101(1), 539–557 (1997)
10. Chaigne, A., Lambourg, C.: Time-domain simulation of damped impacted plates. i. theory and experiments. The Journal of the Acoustical Society of America 109, 1422–1432 (2001)
11. Conan, S., Aramaki, M., Kronland-Martinet, R., Thoret, E., Ystad, S.: Perceptual differences between sounds produced by different continuous interactions. In: Acoustics 2012, April 23-27 (2012)
12. Conan, S., Thoret, E., Aramaki, M., Derrien, O., Gondre, C., Kronland-Martinet, R., Ystad, S.: Navigating in a space of synthesized interaction-sounds: Rubbing, scratching and rolling sounds. To appear in Proc. of the 16th International Conference on Digital Audio Effects (DAFx 2013), Maynooth, Ireland (September 2013)
13. Freed, D.: Auditory correlates of perceived mallet hardness for a set of recorded percussive sound events. The Journal of the Acoustical Society of America 87, 311–322 (1990)
14. Gaver, W.: How do we hear in the world? explorations in ecological acoustics. Ecological psychology 5(4), 285–313 (1993)

15. Gaver, W.: What in the world do we hear?: An ecological approach to auditory event perception. Ecological Psychology 5(1), 1–29 (1993)
16. Giordano, B., McAdams, S.: Material identification of real impact sounds: Effects of size variation in steel, glass, wood, and plexiglass plates. The Journal of the Acoustical Society of America 119, 1171–1181 (2006)
17. Hermes, D.: Synthesis of the sounds produced by rolling balls. Internal IPO report no. 1226, IPO, Center for User-System Interaction, Eindhoven, The Netherlands (September 1998)
18. Houben, M.: The sound of rolling objects, perception of size and speed (2002)
19. Houben, M., Kohlrausch, A., Hermes, D.: Perception of the size and speed of rolling balls by sound. Speech communication 43(4), 331–345 (2004)
20. Houben, M., Kohlrausch, A., Hermes, D.: The contribution of spectral and temporal information to the auditory perception of the size and speed of rolling balls. Acta Acustica United with Acustica 91(6), 1007–1015 (2005)
21. Klatzky, R., Pai, D., Krotkov, E.: Perception of material from contact sounds. Presence: Teleoperators & Virtual Environments 9(4), 399–410 (2000)
22. Lagrange, M., Scavone, G., Depalle, P.: Analysis/synthesis of sounds generated by sustained contact between rigid objects. IEEE Transactions on Audio, Speech, and Language Processing 18(3), 509–518 (2010)
23. Lambourg, C., Chaigne, A., Matignon, D.: Time-domain simulation of damped impacted plates. ii. numerical model and results. The Journal of the Acoustical Society of America 109, 1433–1447 (2001)
24. Lee, J., Depalle, P., Scavone, G.: Analysis/synthesis of rolling sounds using a source-filter approach. In: 13th Int. Conference on Digital Audio Effects (DAFx 2010), Graz, Austria (2010)
25. Lemaitre, G., Heller, L.: Auditory perception of material is fragile while action is strikingly robust. Journal of the Acoustical Society of America 131, 1337–1348 (2012)
26. Marhefka, D., Orin, D.: A compliant contact model with nonlinear damping for simulation of robotic systems. IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans 29(6), 566–572 (1999)
27. McAdams, S., Bigand, E.: Thinking in sound: The cognitive psychology of human audition. Oxford Science Publications (1993)
28. Michaels, C., Carello, C.: Direct perception. Prentice-Hall, Englewood Cliffs (1981)
29. Murphy, E., Lagrange, M., Scavone, G., Depalle, P., Guastavino, C.: Perceptual evaluation of rolling sound synthesis. Acta Acustica united with Acustica 97(5), 840–851 (2011)
30. Rath, M.: An expressive real-time sound model of rolling. In: Proceedings of the 6th International Conference on Digital Audio Effects(DAFx 2003). Citeseer (2003)
31. Rodet, X., Depalle, P., Poirot, G.: Diphone sound synthesis based on spectral envelopes and harmonic/noise excitation functions. In: Proc. 1988 Int. Computer Music Conf., pp. 313–321 (1988)
32. Stoelinga, C., Chaigne, A.: Time-domain modeling and simulation of rolling objects. Acta Acustica united with Acustica 93(2), 290–304 (2007)
33. Stoelinga, C., Hermes, D., Hirschberg, A., Houtsma, A.: Temporal aspects of rolling sounds: A smooth ball approaching the edge of a plate. Acta Acustica united with Acustica 89(5), 809–817 (2003)
34. Thoret, E., Aramaki, M., Gondre, C., Kronland-Martinet, R., Ystad, S.: Controlling a non linear friction model for evocative sound synthesis applications. To appear in Proc. of the 16th International Conference on Digital Audio Effects (DAFx 2013), Maynooth, Ireland (September 2013)

35. Thoret, E., Aramaki, M., Kronland-Martinet, R., Velay, J., Ystad, S.: From shape to sound: sonification of two dimensional curves by reenaction of biological movements. In: 9th International Symposium on Computer Music Modeling and Retrieval, London (2012)
36. Thoret, E., Aramaki, M., Kronland-Martinet, R., Velay, J.-L., Ystad, S.: Reenacting sensorimotor features of drawing movements from friction sounds. In: Aramaki, M., Barthet, M., Kronland-Martinet, R., Ystad, S. (eds.) CMMR 2012. LNCS, vol. 7900, pp. 130–153. Springer, Heidelberg (2013)
37. Tucker, S., Brown, G.: Investigating the perception of the size, shape and material of damped and free vibrating plates. University of Sheffield, Department of Computer Science Technical Report CS-02-10 (2002)
38. Van Den Doel, K., Kry, P., Pai, D.: Foleyautomatic: physically-based sound effects for interactive simulation and animation. In: Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques, pp. 537–544. ACM (2001)
39. Warren, W., Verbrugge, R.: Auditory perception of breaking and bouncing events: A case study in ecological acoustics. Journal of Experimental Psychology: Human Perception and Performance 10(5), 704–712 (1984)