Physically–based real-time modeling of contact sounds

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Abstract

In the following the theory, background and practical use of several real-time sound models of contact scenarios are described. The common audio synthesis core is an algorithm derived from a physically-based impact model, where the acoustic characteristics of colliding objects can be realistically simulated by properly adjusting the physical parameters of the model. Techniques of parameter adjustment are explained for the expression of attributes of ecological hearing, in particular material and position of interaction, starting from physical and/or acoustical specifications. It is shown that in final combination with relevant higher-level structures an efficient implementation of various expressive sound objects is reached. The intuitive practical usability of the models, running in real-time on low cost platforms, is demonstrated, underlining the potential of benefit for a wide range of applications.

1 Introduction

In contrast to a large number of theoretical and practical works in sound synthesis, focusing on the perception and exploitation of conventional musical terms as pitch, timbre or loudness, newer psychoacoustic works (Gaver 1988) point out that the nature of "*every-day listening*" is rather different: From the *ecological* viewpoint, auditory perception delivers information about a listener's surrounding, i.e. objects in this surrounding and their interactions, mostly without awareness of and beyond attributes of musical listening.

Such observations gain in importance, since sound has been recognized to be an effective channel of information within human-computer interfaces (Buxton 1990).

Research in audio for multimedia systems has traditionally focused on techniques related to auralization of environments. Properly designed reverberation and sound spatialization algorithms provide information on the size and shape of an environment, as well as the location of auditory events (Begault 1994). Far less attention has been devoted to the audio *sources*, and the interaction mechanisms that are involved in sound production.

The common use of wave-tables, i.e. the playback of prerecorded sound files, can probably be seen as the standard reaction to the restrictions of former approaches to sound synthesis in the expression of ecological attributes. Sample-based sound though, due to its static nature, is often dissatisfactory in many contexts, such as in Human-Computer-Interaction or in interactive virtual environments, as well as problematic from an esthetic standpoint.

In contrast, we use the term of "acoustic modeling" to refer to the development of "sound objects" that incorporate a (possibly) complex responsive acoustic **behavior**, expressive in the sense of ecological hearing, rather than fixed isolated signals. "Real" sounds hereby serve as an orientation, realistic simulation is not necessarily the perfect goal: simplifications which preserve, possibly exaggerate, certain acoustic aspects, while losing others, considered less important, are often preferred. Besides being more effective in conveying certain information, such "cartoonifications" are often cheaper to implement, just like graphical icons are both, more clear and easier to draw than photo-realistic pictures. Can the idea of audio cartoons suggest an approach to sound design, that fills the gap between simulation or arrangement of concrete sounds and abstract musical expression?

Collisions between solid objects form a wide class of processes significant in everyday listening in the above-mentioned sense. Impacts are basic sub-events of acoustic significance for a large variety of scenarios as e.g. bouncing, rolling, sliding, breaking or machine actions. The extraction/estimation of *structural invariants* (Gaver 1988), i.e. attributes of involved objects such as size, shape, mass, elasticity, surface properties or material, as well as *transformational invariants*, such as velocities, forces and position of interaction points, from impact-based sounds is common experience. Several psychoacoustic studies exist on the topic, accompanied by and connected to results in recent research in sound modeling.

Klatzky *et al.* (Klatzky, Pai, and Krotov 2000) have shown that auditory information can be used in simulated contact with virtual objects, to elicit perception of material. Van den Doel *et al.* (**?**) describe models for audio rendering of collisions and continuous contact (friction and rolling). Convincing results are obtained, however the contact models used in these works do not fully rely on a physical description, and as a consequence the attack transients and the overall realism are affected. Moreover, due to the lack of physical description of contact forces, the control parameters of the sound models are not easily associated to physical dimensions.

A fully physical approach has been adopted by O'Brien *et al.* (O'Brien, Cook, and Essl 2001), who have simulated the behavior of three-dimensional objects using a finite element method. The computation is used for generating both visual and audio animation, hence a high degree of coherence and perceptual consistency can be achieved. On the other hand, finite elements have high computational costs and are possibly "too" accurate, i.e. the models take into account also those sound features that are not perceivable or relevant.

Common to all existing works on the subject is the focus on structural invariants internal to the resonating objects: the significance of a complex transient behavior, reflecting surface depending details of an impact or force and velocity, is rather disregarded. In fact, few is known about the perception of transients. Freed (Freed 1990) developed acoustic parameters related to perceived hardness for a set of recorded percussive sounds; it is uncertain though, what would be a satisfactory connected strategy for the synthesis of impact sounds. Here lies a main point of our basic underlying impact algorithm. Besides the flexible *modal description* of the colliding objects, that forms the basis, and in turn allows immediate use, of existing studies, we consider a physical model of an impact event. This allows us to synthesize convincing impact transients depending on physically meaningful parameters, despite the (current) lack of satisfactory underlying models of their auditory perception.

The impact algorithm, that forms the "audio kernel" of a large variety of sound objects, is derived from the physical model of two resonators interacting through a non-linear contact force. While the velocity and the "hardness"(Avanzini and Rocchesso 2001b) of the contact are immediate control parameters, the modal frequencies of the resonators can be tuned to shapes and materials. Position-dependent interaction is reflected in the varying "weighting" of resonant modes.

A variety of more complex sound objects is realized on top of the basic algorithm: Its physical meaning allows the modeling of convincing sliding- and rolling- scenarios through the integration of surface-(audio)signals under the usage of characteristic "tracking" algorithms. Higher-level control structures exploit the perceptual significance of (statistical or regular) temporal distributions of impacts and their varying attributes: Typical patterns of (ir)regular bouncing objects are explicitly generated. Warren and Verbrugge's investigations (Warren and Verbrugge 1984) of the auditory perception of breaking- and bouncing-events under special consideration of temporal patterns, is the main theoretical psychophysical orientation point for our modeling efforts.

Intuitive handling and the real-time implementation of different objects allow practical access, based on, but not restricted by the boundaries of theoretical foundations.

2 Impact model

2.1 Resonators — "striker", interaction

The resonators are modeled using modal synthesis techniques (Adrien 1991), where a resonating structure is described in terms of its normal modes. The state of the system is here written as the vector of its, generally infinitely many, modal states (as it would, in the spatial description be seen as the vector of states of spatial points). Modal description is in principle equivalent to a description in spatial variables: modal and spatial parameters are related through a linear basis transformation. Modal parameters, though, relate differently to human perception, which is of great importance in terms of implementation and especially of simplification/abstraction[1].

Each modal state $\mathbf{w}_j = \binom{x_j}{\dot{x}_j}$ follows a differential equation

$$\ddot{x}_j + r_j \dot{x}_j + k_j x_j = f_j, \tag{1}$$

where $r_j \geq 0$ and $k_j > 0$ are the damping and the elastic constant of the jth mode, respectively, while f_j is the sum of external forces on the mode. For sufficiently

[1] It might be stated that the spatial description of an object rather refers to its visual appearance whereas modal properties have a closer relationship to auditory perception.

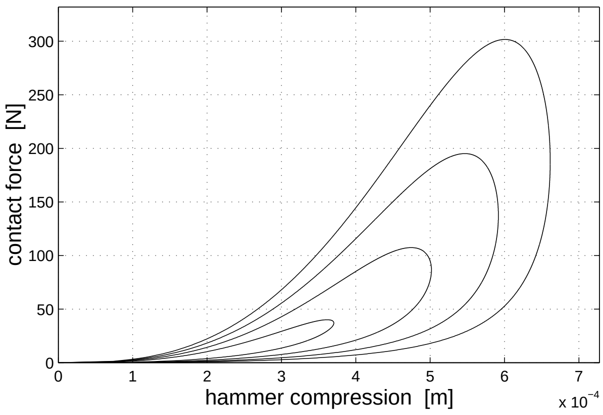

Figure 1: Compression/force characteristics.

small damping ($r_j^2 < 4k_j$), the impulse response $h_j(t)$ of system (1) is given by

$$x_j(t) = h_j(t) = e^{-t/t_j} \sin(\omega_j t) \ . \qquad (2)$$

The resonance frequency ω_j and the decay time t_j are given by

$$k_j = \omega_j^2 + 1/t_j^2, \quad r_j = 2/t_j \ . \qquad (3)$$

Again, for sufficiently small damping the resonance frequency is approximated by $\omega_j \simeq \omega_0 \triangleq \sqrt{k_j}$.

In practice modes are always of finite number n, since the bandwidth of our ears as of any system of processing/reproduction is finite. The transformation from the mode states to a spatial state variable in a point P is then $\mathbf{w}_P = \sum_{j=1}^{n} a_{P\,j}\ \mathbf{w}_j$. Equivalently:

$$x_P = \sum_{j=1}^{n} a_{P\,j} x_j = \mathbf{a}_P \mathbf{x}' \quad and \quad \dot{x}_P = \mathbf{a}_P \dot{\mathbf{x}}' \ , \quad (4)$$

where $\mathbf{x} = (x_1, \ldots, x_n)$ and $\mathbf{a}_P = (a_{P\,1}, \ldots, a_{P\,n})$. In a similar way, a force f applied at a spatial point Q is distributed to the separate modes according to

$$f_j = a_{Q\,j}\ f, \qquad j = 1, \ldots n \qquad (5)$$

In all sound models described here one resonator, in the following referred to as “striker” or “hammer”, is for implementational conveniency further simplified to a freely moving (except during contact with the second resonator) lumped mass. This is the special case of a modal resonator of one undamped resonant mode of frequency 0 and appears as an optimal tradeoff between practical control effort and acoustic result; in fact, in many scenarios of contact the vibration of one involved object is acoustically dominant, while the second one remains comparatively silent. The position of the “striker/hammer” x_h is simply described by the equation

$$m_h \ddot{x}_h = f, \qquad (6)$$

where m_h is its mass.

What is left is an equation which describes the interaction between the two objects. Hunt and Crossley (Hunt and Crossley 1975) proposed a model for the contact force between two colliding objects, under the hypothesis that the contact surface is small:

$$f(x, \dot{x}) = \begin{cases} -kx^{\alpha} - \lambda x^{\alpha} \cdot \dot{x}, & x > 0, \\ 0, & x \leq 0, \end{cases} \qquad (7)$$

where the value of the exponent α depends only on the local geometry around the contact surface. The variable x stands for the hammer compression, i.e. the difference between the resonator displacement and the hammer position. Therefore, when $x > 0$ the two objects are in contact. Marhefka and Orin (Marhefka and Orin 1999) have used this model for describing contact with the environment in dynamic simulations of robotic systems, and have shown that it provides realistic results. Figure 1 shows the penetration/force characteristics for a hammer hitting a hard surface with various impact velocities. Note that hysteresis occur, i.e. the paths during loading and unloading are different. This effect comes from the presence of a dissipative term in Eq. (7).

2.2 Properties

When the system is discretized, the modal resonator appears as a parallel filter bank of N second–order resonant low-pass filters, each accounting for one specific mode of the resonator. The filter parameters (center-frequency and quality factor) are accessed through the physical quantities r_j, k_j described above. Due to the non-linear nature of the contact force, computational problems occur in the numerical hammer-resonator system. These can be handled by computing the contact force iteratively at each time step (Avanzini and Rocchesso 2001a; Avanzini and Rocchesso 2001b).

The elementary physical basis of the impact algorithm adds an amount of responsiveness that is not reached by sample-based sounds neither by models that work with preassumed force-profiles. Figure 2(a) shows an example output from the model, in which the impact occurs when the resonator is already oscillating: the interaction, and consequently the contact force profile, differs from the case when the resonator is not in motion before collision. These details of “liveliness” are lost using pre-stored contact force profiles as in (**?**). Figure 2(b) shows an example of “hard collision”. This has been obtained by giving a very high value to k in Eq. (7), while every other parameter of the model has the same values as in Fig. 2(a). It can be noticed that several micro-collisions take place during a single impact. This is qualitatively in accordance with the remarks by van del Doel *et al.* about hard collisions (**?**).

A study on perceived material quality (Avanzini and Rocchesso 2001b) has shown that the contact time

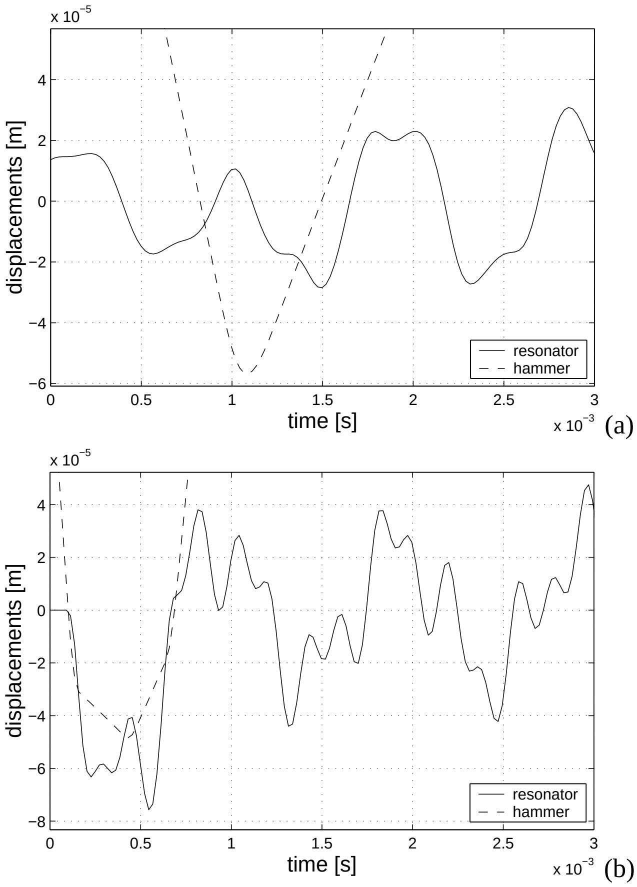

Figure 2: Numerical simulations; (a) impact on an oscillating resonator; (b) micro-impacts in a hard collision. Intersections between the solid and the dashed lines denote start/release of contact.

(i.e. the time after which the hammer separates from the resonator) can be controlled using the physical parameters. Specifically the ratio m_h/k is found to be the most relevant parameter in controlling contact time.

Gesture-based control models can be designed for the sound synthesis algorithm, where the initial velocity of the striker is a main control parameter. In a recent work, a virtual percussion instrument has been designed, where the sound model is based on the hammer-resonator system described above and the control model is implemented through a gestural interface (Marshall, Rath, and Moynihan 2002).

The subtle sound nuances achieved by the model provide a rich timbral palette that can be very useful in sonification and auditory display. Its responsiveness to user gestures is especially suitable for sonic feedback, where the audio information should give confirmation about the extent and quality of a performed action. These qualities is inherited by higher-level sound-objects based on the algorithm, described in section 4.

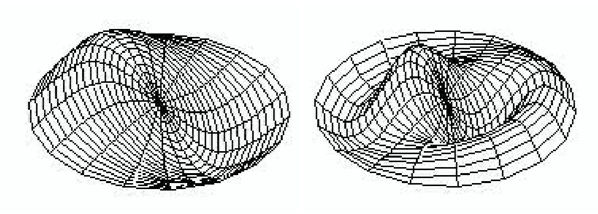

Figure 3: A circular membrane displaced from its rest position along the axes of mode(1,1) (left) and mode(1,2) (right). The frequencies of vibration along these axes are 1.593 and 2.917 times that of mode(0,1) (the "fundamental").

3 Resonator Attributes

Figure 3 shows a membrane in states of displacement from its rest position along isolated modal axes. The distance of each point of the membrane from the "rest plane" is proportional to the weighting factor of the mode at this position. Note that the section lines of the mode-shape with the rest plane stay fixed through the whole movement along this modal axis, since the weighting factors at these positions are obviously 0. Correspondingly, an external force applied at these node lines does not excite the mode at all.

Position dependent weighting factors

There are several possible approaches to identify the position dependent weights. In the case of a finite one dimensional system of point masses with linear interaction forces, modal parameters are exactly found through standard matrix calculations. Most systems of interest of course do not fit these assumptions. In some cases the differential equations of distributed systems can be solved analytically, giving the modal parameters; this holds for several symmetrical problems as circular or rectangular membranes.

Alternatively, either accurate numerical simulations (e.g. wave-guide mesh methods) or "real" physical measurements can be used. Impulse responses computed (or recorded) at different points then form a basis for the extraction of modal parameters. The acoustic "robustness" of the modal description allows convincing approximations on the basis of microphone-recorded signals of e.g. an objects struck at different points, despite all the involved inaccuracies: spatially distributed interaction, as well as wave distribution through air, provide signals that are quite far from impulse/frequency responses at single points.

The following considerations illuminate the possibility of aforementioned estimations. Equations (1) and (2) correspond to the frequency response of a resonant low-pass filter. The transfer function connected to one or a pair of spatial points of the system is a weighted sum of these responses with position dependent factors. Even in non-ideal recording conditions, the prominent modes can be identified from peaks in the response. The level of the peak j reflects the position dependent weight while its width is related to the time factor t_j. Decay times can though be extracted more easily from STFT values at different temporal points. The clear perceptual character of these parameters finally allows "tuning by ear" which in many situations is the final judging instance.

Qualitative observations on modal shapes, exemplified in figure 3, can be effectively used in a context of cartoonification: for modes of higher frequencies the number of *nodes* increases and its spatial distance accordingly decreases.

1. One consequence is that for higher modes even small inaccuracies in interaction or pickup position may result in strongly different weighting factors, so that an element of randomization can here add "naturalness".

2. For interaction positions close to a boundary, which is a common node for all modes, the lowest modes gradually disappear and higher modes (with smaller "regions of weight") relatively gain in importance. This phenomenon can be well noticed for a drum: if the membrane is struck close to the rim the excited sound gets "sharper", as the energy distribution in the frequency spectrum gets shifted upwards ("rimshots"). For a clamped bar higher partials are dominant near the fixed end, whereas lower frequencies are stronger for strokes close to the free vibrating boundary (noticeable in sound adjustments of electromechanical pianos).

Similar considerations apply to points of symmetry: some resonant modes, those with modal shapes antisymmetric to central axes, are not present in the center of a round or square membrane. They consequently disappear "bottom–up" when approaching the center point.

Material expression

Sounds identified with certain materials are effectively achievable with our algorithm. This may correspond to its capability to reflect resonance- *and* interaction-, that is here: surface- properties. Further higher-level modeling efforts strongly rest and rely on a convincing basis of material attributes (in particular "breaking" scenarios see section 4). From a current pragmatic standpoint it has to be noted that existing studies of material perception start from somewhat opposite assumptions and consequently lead to different results (see section 1).

The sound model has been tested in previous studies in order to assess its ability to convey perceptually relevant information to a listener. A study on materials (Avanzini and Rocchesso 2001a) has shown that the decay time is the most salient cue for material perception. This is very much in accordance with results by Klatzky *et al.* (Klatzky, Pai, and Krotov 2000); however, the physical model used here is advantageous over using a signal-based sound model as in (Klatzky, Pai, and Krotov 2000), in that more realistic attack transients are obtained. A linear dependency of decay time over frequency, expressed through a material-specific coefficient of internal friction, as developed in a work of Wildes and Richard (Wildes and Richards 1988), seemed to be the most effective approach to acoustic expression of material. Figure 4 shows a part of a PD patch that specifies decay time parameters for modal frequencies after an internal friction parameter and an additional coefficient representing external frictional losses. This method, that has been used (van den Doel, Kry, and Pai 2001) and supported through psychoacoustic testing (Klatzky, Pai, and Krotkov 2000) before, is here completed with the described physically-based model of the impact itself. The resulting capability to include further (material-/surface-specific) interaction parameters, such as hardness of contact or "stickiness" fundamentally contributes towards expressivity and realism. Of course these examinations would open up a wide field for systematic testing. One should also keep in mind that the linear decay/frequency dependency is one possible approximation and psychoacoustic studies also show a slight influence of frequency ranges on material impression (Klatzky, Pai, and Krotkov 2000). Practical sound design examples can benefit from intuitive deviations of modal parameters from exact theory-based values.

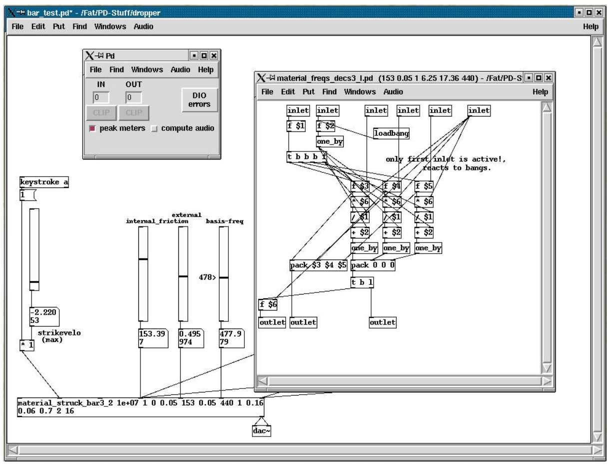

Figure 4: Example of the impact module with a resonator tuned according to the theory of a thin bar. The sub-patch calculates the decay times, according to the partial frequencies and coefficients of external and (material-specific) internal friction.

4 Higher-level modeling

Rolling, Sliding

According to its clear physical meaning the fundamental algorithm can be exploited for the modeling of more complex contact scenarios, if the acoustically relevant interaction force is (approximately) 1-

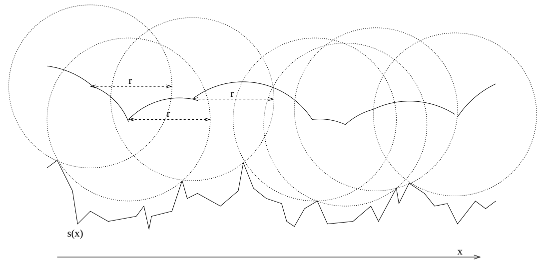

Figure 5: Sketch of the effective offset-curve, resulting from the surface $s(x)$. The condition on the surface to be expressible as a function of x is clearly unproblematic in a "rolling" scenario.

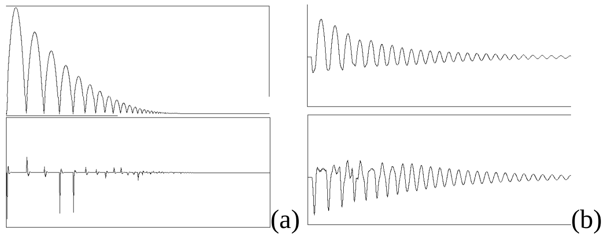

Figure 6: An inertial mass "bouncing" on a two-mode resonator. (b) focuses on the final state of the process: The two interacting objects finally stay in constant contact, a clear difference to simply retriggering.

dimensional and describable by the underlying equation 7. This is true to a certain extent to actions of sliding and particularly rolling (Rath 2002). An external, typically constant or slowly modulated, force-term, pressing together both resonators, is added to the interaction force (given by equation 7) and the difference variable obtains an offset term given by the surface-profile; this surface-signal might be taken from microscopic measurements — in our cases it is filtered noise, generated after statistical considerations (for details see (Rath 2002)). Any audio signal can be used as a representation of a fictional surface, analogous to the coding of audio signals on a vinyl record.

Of course, the pattern of contact of the resonators is also strongly influenced by their macroscopic geometry, an important point, especially in the case of rolling, that has to be accounted for by special preprocessing of the surface signal. The derivation and several practical strategies to realize this computationally complex "filtering" notion are explained in detail in (Rath 2002).

Finally, listening-experience and psychoacoustic studies show the relevance of (quasi-)periodic low-frequency modulations in rolling-sounds, due to global geometric dissymmetries; these are achieved immediately in our model by according modulations of the input signals of external force and velocity and strongly contribute to the expressivity of the resulting sound.

Bouncing, Breaking

The inclusion of an external force term as necessary for the above-described rolling- and sliding-objects, can result in macroscopic temporal patterns of impact events, a phenomenon that impressively aggravates the responsive potential of the objects. This implicit generation of "bouncing"-patterns on the basis of the impact algorithm though shows to be unsatisfying and too limited for a wider range of scenarios: The macro-temporal pattern can not be intuitively controlled, but cross-depends on the elementary impact parameters. More important, the 1-dimensionality leads to regular patterns as occurring in reality only for perfectly spherical objects. A higher-level "bouncer" control structure is thus used to explicitely create typical patterns of falling objects. Following our approach of cartoonification, the bouncer is controlled through a set of parameters that allow to express perceptually relevant attributes of a virtual sound source, as regularity, damping or shape, while avoiding the overhead in practical and computational complexity of a fully detailed physical simulation (see (Rath 2002) for details of theoretical background and practical handling).

In Warren and Verbrugge's study of the auditory perception of breaking- and bouncing-events (Warren and Verbrugge 1984), it is shown that sound artifacts created through layering of recorded collision sounds, were identified as bouncing or breaking scenarios, depending on their homogeneity and the regularity and density of their temporal distribution. These results are the starting point of our according modeling-efforts. In fact, the "bouncer" module shows to be effective for the synthesis of sound cartoons of breaking, by a slight extension of its parameter range as originally used for bouncing-sounds. The temporal density of impact events is here set to a decreasing behavior, i.e. opposite to its tendency in the bouncing-case. Also, in agreement with Warren and Verbrugge's examination, a short initial noise impulse shows to contribute to a "breaking" impression. (For details see (Rath 2002).)

5 Implementation and use

The model has been implemented as a module for the real–time sound processing software *PD*[2]. Controls are handled with the temporal precision of an audio buffer length; values for the *PD* buffer-size are e.g. 32 or 64 samples, that provide temporal accuracies of ≈ 0.75 ms and ≈ 1.5 ms, respectively. The iterative algorithm used for solving the non-linear interaction has been observed to exhibit a high speed of convergence: the number of iterations at each time step is never higher than four. As a consequence, the module runs in real-time on low-cost platforms.

The quality of the audio generated from the model has been assessed through both informal evaluations and formal listening tests (Avanzini and Rocchesso

[2] `http://www.pure-data.org`

2001a): in general, the impact sounds are perceived as realistic. The control on the impact location provides convincing results.

The impact model is being used as the kernel of a variety of sound models. It has been shown that certain sounds are very effective to convey information about continuous processes. For instance, the sound of a vessel being filled is quite a precise display of the level of liquid (Vicario 2001). Similarly, sliding, rolling, scraping, and crumpling are all phenomena that are easily recognized by ear, thus being perfect candidates for auditory display. If properly cartoonified, they can be used as dynamic auditory icons that give information about events and processes. Just by temporal organization and dynamic control of micro-impacts, we have been developing sound models for a variety of these phenomena.

Again, the veridical control that we can exert on the contact model, and the possibility to manipulate the control variables in real-time, give to the sound designer much more flexibility. In the end the sound cartoons of complex processes such as scraping or rolling turn out to be more engaging and pleasant as compared to the results of models based on samples (**?**).

6 Acknowledgments

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