AN INTRODUCTORY CATALOG OF COMPUTER-SYNTHESIZED CONTACT SOUNDS, IN REAL-TIME

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ABSTRACT

As part of the SOb European project several cartoon models of contact sounds of solid bodies, "hitting", "bouncing", "dropping", "breaking", "rolling", have been developed and implemented as modules (and sub-patches) for free real-time sound software `pd` [1]. The models are accessed through perceptually meaningful parameters and run with low computational load on standard PC hardware.

The underlying idea of *cartoonification*, its motivation and background in psychoacoustic research are sketched first. The main common sound-core of most models, a physics-based algorithm of impact-interaction with interacting resonators in modal description, is shortly presented. The impact module is embedded in patches of higher-level control to model more complex contact scenarios. The structure, use and potential of the resulting sound objects is described.

While the results are a possible basis for reactive sonic interfaces in Human-Computer-Interaction, they can as well be exploited for musical purposes.
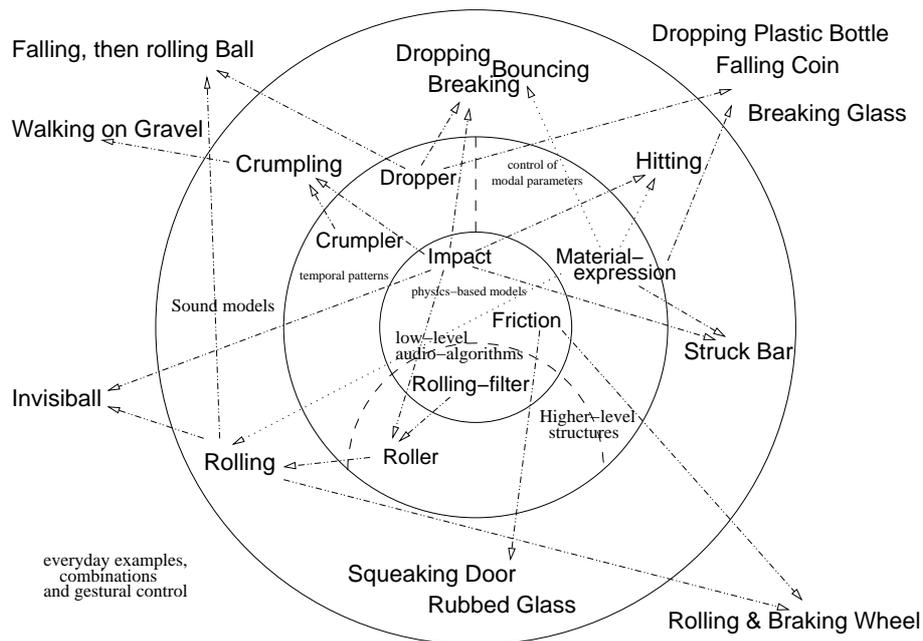
1. CATALOG

Figure 1: Overview of real-time sound models of contact scenarios and their underlying structures, as developed during the course of the SOb project. The graphical layout in nested (circular) fields reflects the structural hierarchy: Physics- and geometrically-based low-level audio algorithms in the center, completed with surrounding higher-level objects, resulting sound models in the largest circle and finally more concrete and complex example-scenarios, that may also envolve gestural control. Arrows indicate dependencies and are to be read as "contributes"/"used to realize".

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[1] `http://iem.kug.ac.at/pd/`

2. INTRODUCTION

In 1969, Risset published a ground-breaking catalog of computer-synthesized sounds [1], which served the purpose of illustrating the emerging techniques of sound analysis and synthesis. Those examples and studies are still influential for composers and sound scientists, especially those working with signal-processing tools and in the context of musical sounds. The discipline of psychoacoustics has provided, over the years, a solid support to connect signal processing to human perception.

A new stream of studies started in the early eighties from the observation that everyday listening is different from musical listening [2]. Both new psychoacoustic and sound modeling methods and results are needed for this new framework. On the perceptual side, the viewpoint of ecological psychology is very useful [3]. On the modeling side, the physically-based modeling paradigm seems to be the best sound production strategy to address everyday listening in interactive applications.

The EU-funded project "the Sounding Object" (SOb) [2] was launched in 2001 to provide a corpus of knowledge in everyday sound perception, accompanied by suitable new methods and tools for physics-based sound modeling and for high-level control of these models.

The SOb project aims at "sounding objects" that incorporate a (possibly) complex responsive acoustic **behavior**, expressive in the sense of ecological hearing, rather than the (re-)production of fixed isolated signals. Although "real" sounds hereby serve as an orientation, realistic simulation is not necessarily the perfect goal: simplifications which preserve and 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.

Physical modeling naturally relates to synthesis controlled in terms of ecological parameters. The straight approach though, the description of a given physical system through differential equations and their numerical solution, often leads to (possibly highly) realistic simulations that are computationally expensive and lack flexibility and generality. We thus combine closely physics-based models in the above sense with structures that remind of classical techniques of sound synthesis, trying to integrate ecological expressivity, flexibility and computational efficiency.

Contacts of solid bodies form a large class of sound-emitting processes in every-day surroundings. The perception of ecological attributes, like material and size of involved objects and their way of interaction, hitting, sliding, rolling..., from contact sounds is common experience and has been examined by psychoacoustic studies. Our works show that, from the standpoint of cartoonification, many typical forms of contact-interaction can be successfully modeled on the basis of a physically founded but "abstracted", flexible and efficient one-dimensional impact or friction algorithm. Specific characteristics of the macroscopic scenarios which are of high perceptual relevance are modeled explicitly, for instance as macro-temporal distributions of micro-impacts.

This paper is intended to be a explanatory guide to our collection of sound models and examples, as they are available nowadays

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from the SOb project website as `pd` plugins and patches. Detailed explanations of the inner structure and the development of all models can be found in [4]. All contact sound models are based on low-level models of basic interactions: impacts and frictions, which are described in sections 3.1 and 3.2. Higher-level models describing phenomena with complex temporal patterns are presented in section 4. Finally, section 5 briefly gives some examples of how the sound models can be associated to everyday objects, thus providing their typical sonic behavior in an interactive, real-time fashion.

3. THE LOW-LEVEL PHYSICS-BASED MODELS

3.1. Impact

In contrast to several studies of contact sounds of solid bodies that focus on the resonance behavior of interacting objects and widely ignore the transient state of the event, our approach is based on a physical description of impact interaction processes [5]. This physical model involves a degree of simplification and abstraction that implies efficient implementation as well as adaption to a broad range of impact events.

We consider two resonating objects and assume that their interaction depends on the difference x of two (1-dimensional) variables connected to each object. In the standard case of examined movements in one spatial direction, x is the distance variable in that direction (negative distance $\triangleq$ contact). Possible simultaneous interaction along other dimensions are excluded at this stage. This leads to a compact efficient algorithm that strikes the main interaction properties. The impact force f is stated as a nonlinear term in x (and $\dot{x}$):

$$f(x(t), \dot{x}(t)) = \begin{cases} k(-x(t))^\alpha + \lambda(-x(t))^\alpha \cdot (-\dot{x}(t)), & x < 0 \\ 0, & x \geq 0 \end{cases} \quad (1)$$

Here, k is the elasticity constant, i.e. the hardness of the impact. α, the exponent of the non-linear terms, shapes the dynamic behavior of the interaction (i.e. the influence of initial velocity), while λ controls the dissipation of energy during contact, accounting for friction loss. One inlet of the `impact_...`[3] modules takes a list of `interactor`-parameters containing the aforementioned values (in the same order).

Alternative versions, "`linpact_...`" exist with a simpler, linear, force term,

$$f(x(t), \dot{x}(t)) = \begin{cases} -kx(t) - r\dot{x}(t), & x < 0 \\ 0, & x \geq 0 \end{cases} \quad (2)$$

(and accordingly only two `interactor`-parameters k and r), that trade richness in detail for reduced computational cost.

The two interacting, resonating objects are built under the premises of modal synthesis [6] [4]. This formulation supports particularly well our main design approach for its physical generality and, at the same time, for its intuitive acoustic meaning. One `resonator` is here characterized by the number of its modes (which

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[3]The difference between `impact_modalb` and `impact_2modalb` is explained later in the section.

[4]In fact, plugins are realized in a modular structure, that enables the connection of numerous different `resonators` as well as `interactors`. Digital waveguide resonators are in preparation; linearized impact and friction are the additional existing `interactors`. All modules so far share the modal `resonator`-functions.

can be chosen freely as an argument given at module-creation) and for each mode the three modal parameters: mode-frequency, exponential decay-time and level ("weight") of the mode at the point of interaction. Accordingly the `impact_/linpact_...` modules have inputs for lists (of length "number of modes") of frequencies, decay-times and `weighting-factors`. It is often satisfactory and more convenient to use the modules `impact_modal` and `linpact_modal`, where (in contrast to `impact_2modal` and `linpact_2modal`) the first `resonator` is reduced to an inertial (point-)mass[5] and characterized only by one ("mass"-)parameter. This practical and computational simplification parallels the notion that in many practical contact scenarios the vibration of one involved object is hardly or not perceived.

Further, for each resonator, an arbitrary number of "`pickups`" can be defined, which are characterized by lists, given at one inlet, of `weighting-factors` (for all modes). The first `pickup` is identical with the interaction-point (and always exists).

Finally, all modules have three audio inlets, for the input of signals representing external forces on both resonators (again at the point of interaction) and an additional `offset`, used mainly for surface profiles in rolling-/sliding-models.

3.2. Friction

For friction modeling, we use a computational structure very similar to the one used for impacts. The `pd` plugin is called `friction_2modalb`.

The underlying model describes the average behavior of a multitude of micro-contacts made by hypothetical bristles extending from each of two sliding surfaces. When a modal decomposition is adopted for both interacting objects, the equations are

$$
\begin{cases}
m_{ei}\ddot{x}_{ei} + r_{ei}\dot{x}_{ei} + k_{ei}x_{ei} = f_{ee} - f_f, & (i = 1 \dots N_e) \\
m_{rj}\ddot{x}_{rj} + r_{rj}\dot{x}_{rj} + k_{rj}x_{rj} = f_{re} + f_f, & (j = 1 \dots N_r) \\
v = \sum_{i=1}^{N_e} \dot{x}_{ei} - \sum_{j=1}^{N_r} \dot{x}_{rj}, & \text{(relative velocity)} \\
\dot{z} = f_{NL}(v, z) = v\left[1 - \alpha(z, v)\dfrac{z}{z_{ss}(v)}\right], \\
f_f = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 v, & \text{(friction force)}
\end{cases}
$$

$$(3)$$

where the x variables represent the modal displacements, while z is the mean bristle displacement. The terms f_{ee} and f_{re}, as indicated by e in the second subscript, represent external forces. As far as the form of functions α and z_{ss} is concerned, we adopt a couple of previously proposed functions[7].

High-level interactions between the user and the audio objects rely mainly upon three interaction parameters. These are the external forces f_{ee} and f_{re} (see equations (3)) acting on each of the two objects, which are tangential to the sliding direction, and the normal force f_N between the two objects. The remaining parameters belong to a lower level control layer, as they are less likely to be touched by the user and have to be tuned at the sound design level.

Such low-level parameters can be grouped into two subsets, depending on whether they are related to the resonators' internal properties or to the interaction mechanism. Each mode of the two resonating objects is tuned according to its center frequency and

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[5]This is the special case of a modal resonator with only one resonant mode of frequency 0 and infinite decay time (undamped).
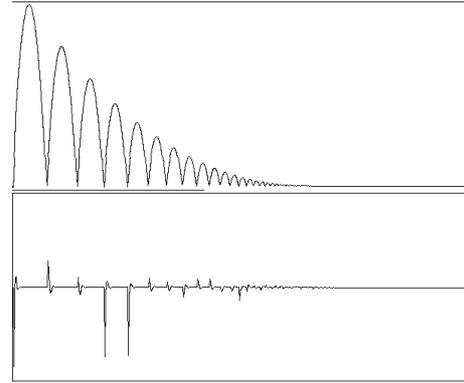

Figure 2: Temporal movement of an inertial mass (above) "bouncing" on a two-mode resonator (at `pickup-point`, below).

decay time. Additionally, a modal gain (which is inversely proportional to the modal mass) can be set for each resonator mode, and controls the extent to which the mode can be excited during the interaction.

A second subset of low-level parameters relates to the interaction force specification. The triple $(\sigma_0, \sigma_1, \sigma_2)$ (see equations (3)) define the bristle stiffness, the bristle internal dissipation, and the viscous friction, and therefore affects the characteristics of signal transients as well as the ease in establishing stick-slip motion. A triple of parameters is used to set the shape of the curve z_{ss}. Specifically, the Coulomb force and the stiction force are related to the normal force through the equations $f_s = \mu_s f_N$ and $f_c = \mu_d f_N$, where μ_s and μ_d are the static and dynamic friction coefficients. Finally, the breakaway displacement z_{ba} is also influenced by the normal force. In order for the function $\alpha(v, z)$ to be well defined, the inequality $z_{ba} < z_{ss}(v) \forall v$ must hold. Since $\min_v z_{ss}(v) = f_c/\sigma_0$, a suitable mapping between f_N and z_{ba} is

$$z_{ba} = cf_c/\sigma_0 = c\mu_d f_N/\sigma_0, \quad \text{with} \quad c < 1. \quad (4)$$

4. HIGHER-LEVEL STRUCTURES

4.1. Bouncing, Dropping, Breaking

Short acoustic events like impacts can strongly gain or change in expressive content, when set in an appropriate temporal context. One example is the grouping of impacts in a "bouncing" pattern, as it results from a constant external (gravity-)force term.

The one-dimensionality of the impact algorithm only allows the immediate simulation of symmetrical, basically spherical, bouncing objects; these simulations through an external gravity term are very realistic in detail, "too realistic" from a standpoint of *cartoonification*: The exact (accelerating) tempo of bouncing is coupled to the impact parameters, and simplifications on the elementary sound level necessarily affect the higher level pattern. A strict physical simulation of irregular bouncing objects on the other hand, would be highly complex to control and implement, computational "overkill". Instead, an explicit modeling of typical bouncing-patterns leads to *cartoonifications*, that are efficient to implement and able to express ecological attributes like regularity/irregularity of the bouncing object. The main notions behind the structure and parameters of the "`dropper`" object are shortly sketched in the following.

The first basic principle behind the process is the loss of macro-kinetic energy of the global vertical, horizontal and rotational movement, in friction and microscopic (e.g. acoustic) vibration. These loss-terms in exactness are different for each impact, and can in this detail only be found from an elementary simulation as above. Under the assumption, that the loss of (macro-)energy with each bounce is proportional to the remaining kinetic energy, we receive an exponentially (in the number of reflections) decaying energy term. If we further for spherical bouncing objects concentrate on the vertical movement and ignore the horizontal and rotational terms as independent, the kinetic energy at floor level is proportional to the square roots of collision velocity and the duration of the following bounce. We thus arrive at analogous exponentially decaying terms for impact velocities and temporal intervals in a regular bouncing movement. The implementation of this basic scheme in fact proved to be convincing in comparison with the afore-described implicit simulation (compare figure 2) as well as recordings of bouncing (round) wooden balls. For irregular objects, energy can be transferred between the vertical, horizontal and rotational terms, of which only the vertical velocity (and therefore the maximum height) contributes a simple term to the impact intervals and velocities, while the contribution of the rotational movement is not expressible in a simple form (and that of the horizontal movement is basically zero). Energy transfer thus results in deviations of both, impact-intervals and -velocities, from, but generally bounded by, the (exponentially decaying) values of the regular case. Similarly, also the effective relative masses and the `weighting-factors` of resonant modes are modulated through the rotation (and therefore changing contact points) of an irregular object. Summing up, while generally the exact movement in the non-spheric case can only be simulated through a detailed solution of the underlying differential equations, which would not make sense in our context of real-time interactivity[6], controlled-random patterns of impact parameters can generate expressive cartoonifications. Another important observation are static stages in the bouncing movement also of non-spherical shapes with certain symmetries of regular aspects (e.g. such as disks or cubes). In these cases the transfer of energy between the vertical, horizontal and rotational terms can take place in regular patterns, closely related to those of spherical objects. This phenomenon is exploited in some modeling examples; often however, such movements include rolling aspects, suggesting a potential improvement through integration of rolling models. A very prominent sound example with an initial "random"- and a final regular stage is that of a falling coin.

Following the previous observations, the "`dropper`" generates temporal patterns of impact velocities triggered by a starting message. Control parameters are:

1. The time between the first two reflections, representing the initial falling-height/-velocity, together with

2. the initial impact velocity.

3. The acceleration factor is the quotient of two following maximal "bounce-intervals" and describes the amount of microscopic energy loss/transfer with each reflection, thus the speed of the exponential time sequence.

4. The velocity factor is defined analogously.

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[6]Also, it seems questionable, how precisely shapes of bouncing objects (except for sphericity) can be recognized acoustically?

Note that these parameters should for a spherical object be equal (see above), while in exactness being varied (in dependence of actual impact velocities) in the general case. In a context of cartoon-based auditory display they can be effectively used in a rather intuitive free fashion.

5. Two parameters specify the range of random deviation below the (exponentially decaying) maxima for temporal intervals resp. impact velocities. The irregularity/sphericity of an object's shape is modeled in this way.

6. A threshold parameter controls, when the accelerating pattern is stopped, and a "terminating bang" is sent, that can e.g. trigger a following stage of the bouncing process.

Warren and Verbrugge [8] study on the perception of breaking- and bouncing-scenarios is a starting point for our related modeling efforts. They showed, that sound artefacts, 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.

Again the main ideas behind the structure of the breaking-model are shortly sketched: Typical fragments of rupture are of highly irregular form and rather anelastic, and tend to "nod" rather than bounce, i.e. perform a decelerating instead of accelerating movement. It is further on important to keep in mind that emitted fragments mutually collide, and that the number of such mutual collisions rapidly decreases, starting with a massive initial density; those collisions do not describe bouncing patterns at all. Following these examinations the breaking-model was realized by use of the `dropper` with high values of "randomness", and a quickly **decreasing** temporal density, i.e. a time-factor > 1, set "opposite" to the original range for bouncing movements. Supporting Warren and Verbrugge's examination, a short noise impulse added to the attack portion of the pattern underlined the breaking character.

As another insight during the modeling process, several sound attributes showed to be important. Temporally identically grouped impacts seem to be less identifiable as a breaking event, when tuned to a metallic character in their modal settings; this may correspond to the fact that breaking metal objects are rather far from everyday experience. Also, extreme mass relations of "striker" and struck resonator in the impact settings, led to more convincing results. Again, this is in correspondence with typical situations of breakage: a concrete floor has a practically infinite inertia in comparison to a bottle of glass.

4.2. Rolling

Among the various common mechanical interactions between solid objects, "rolling" scenarios form a category that seems to be characteristic also from the auditory viewpoint: Everyday experience tells that the sound produced by a rolling object is often recognizable as such, and in general clearly distinct from sounds of slipping, sliding or scratching interactions, even of the same objects. This may be due to the nature of rolling as the most prominent **continuous** interaction process, where the mutual force on the involved objects is described as an impact without additional perpendicular friction forces.

Consequently, the impact-algorithm has been embedded in a complex higher-level structure to reach an efficient cartoonification, that can express various ecological attributes of rolling-
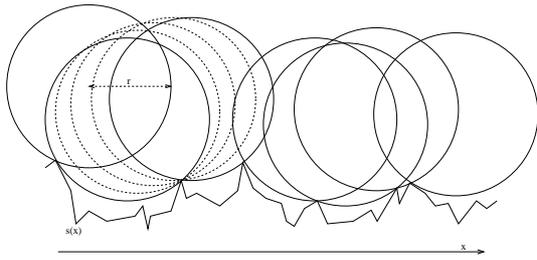
Figure 3: Sketch of the fictional movement of a ball, perfectly following a surface profile s(x). Relative dimensions are highly exaggerated for a clearer view. Note that this is **not** the de-facto movement; this idealization is used to derive the `offset-curve` to be used by the impact-model.

Figure 4: Sketch of the effective `offset-curve`, resulting from the surface $s(x)$.

scenarios: material, size and shape of the involved objects, as well as velocity or acceleration/deceleration (*transformational attributes* [2]). The main observations behind the development and structure of the model are presented shortly:

4.2.1. Rolling interaction with the impact-model as lowest-level building block on a driving `offset-curve`

Rolling-contact between two objects is restricted to distinct points: the supporting surface is **not** fully "traced"/followed, nor is the surface of the rolling object. Figure 3 sketches the idea; the rolling object is here assumed to be locally spherical without "microscopic" surface details. These assumptions are unproblematic, since the micro details of the surface of the rolling object can be simply added to the second surface (to roll on) and the radius of the remaining "smoothed macroscopic" curve could be varied; in conjunction with following notions, even an assumed constant radius however showed to be satisfactory.

The actual movement of the rolling object differs from the idealization of figure 3 due to inertia and elasticity. In fact, it's exactly the consequences of these physical properties, which are described by, and substantiate the use of the impact model(-equations). It is further important to notice that, in contrast to slipping-, sliding- or scratching-actions, the interaction force on the two objects involved in a simple rolling-scenario is approximately perpendicular to the contact surface (the macroscopic mean curve), pointing along the connection line of the momentary point of contact and the "center of the rolling object". This fact is not reflected in the sketches, since here relative dimensions are highly unrealistic, exaggerated for purposes of display). Summing up, the final vertical movement of the center of the ball can be approximated by use of the one-dimensional impact-model with the `offset-curve` shown in figure 4.

In a naive approach, the calculation of contact points is computationally highly demanding: In each point x along the surface curve $s(q)$[7], i.e. for each sampling point in our practical discrete case (at audio rate), the following condition, which describes the momentary point of contact p_x, would need to be solved:

$$f_x(p_x) = max_{q \in [x-r, x+r]} f_x(q) \qquad where \qquad (5)$$
$$f_x(q) \triangleq s(q) + \sqrt{r^2 - (q-x)^2}, \quad q \in [x-r, x+r]$$

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[7]Here we use the unproblematic assumption that the surface curve is presentable as a real function $s : I \longmapsto R, I \subseteq R$ an interval.
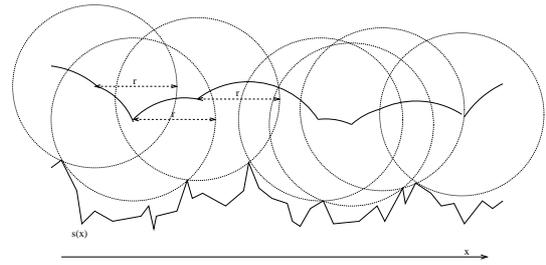
To facilitate a practical, real-time, implementation, a "smart" algorithm had to be developed, that reduces the number of calculations/comparisons by factors up to 1000. The ideal `offset-curve` is then calculated from the coordinates of the contact points.

4.2.2. Surface profile

The surface-signal which is processed by a "rolling-filter" as above might be derived through scanning/sampling of "real" surfaces. A flexible statistics-based generation though is preferable in our context over the sumptuous, static storage of fixed profiles. One such approach is *fractal noise*, i.e. noise with a $1/f^\beta$ power spectrum, the real parameter β reflecting the fractal dimension or roughness. Practical results of modeling following the so-far developed methods however became much more convincing, when the bandwidth of the surface-signal was strongly limited. This does not surprise, when one keeps in mind that typical surfaces of objects involved in rolling scenarios, are generally smoothed to high degree. (In fact, it seems hard to imagine, what e.g. an uncut raw stone rolling on another surface, typically modeled as a fractal, let's say a small scale reproduction of the alps, would sound like?) Smoothing on a large scale, e.g. cutting and arranging pieces of stone for a stone floor, corresponds to high-pass-filtering, while smoothing on a microscopic level, e.g. polishing of stones, can approximately be seen as low-pass-filtering. In connection with this resulting bandpass, the $1/f^\beta$ characteristics of the initial noise signal lost in significance. Band-pass filtered white noise thus was chosen as a cheap and efficient solution; it can eventually be enhanced by an additional second-order filter, whose steepness finally represents a "microscopic" degree of roughness as a very coarse approximation of the fractal spectrum.

Of course, the parameters of the impact itself, in particular the elasticity constant k, can/must also be carefully adjusted to surface-, e.g. material properties and strongly contribute to the expressiveness of the model.

4.2.3. Higher-level features

Typical scenarios of rolling tend to show characteristic "macroscopic" acoustic features, that appear to be of high perceptual relevance, especially for velocity-expression. Macro-temporal periodicities result from typical patterns of more or less regular nature as found on many "ground" surfaces (such as joints of stone- or wooden floors, the periodic textures of textiles or the pseudo-periodic furrows in wooden boards). Seemingly even more important, for rolling objects, that are not perfectly spherical (in the sec-

tion relevant for the movement), the velocity of the point of contact on both surfaces and the effective force pressing the rolling object to the ground vary periodically. In order to model such deviations from perfect sphericity, these two parameters must be modulated, our practical experience showing a higher significance of pressing-force; a good choice are obviously sinusoidal or other narrow-band modulation signals (since objects that differ too much from a spherical shape, that are too edgy, don't roll!). Of course all (quasi-)periodic modulations have to reflect the rolling-velocity in their frequency.

Finally it is to be noted that, like in everyday listening, acoustic rolling scenarios are recognized and accepted more easily with "typical dynamics": As an example, consider the sound of a falling marble, that bounces until constant contact to the ground is reached, now the rolling action gets acoustically clear and the average speed slowly decays to zero.

4.3. Crumpling

Like most other sounds presented in this catalog, `crumpling` results from providing the impact model with a control layer. Since `crumpling` does not model physical contacts between solid objects, but rather special time sequences of bends, the use of closed-form formulas expliciting interaction mechanisms can be avoided.

Impacts are triggered following stochastic laws which are derived from the physics of crumpling [9]. Such laws rule the dynamic and temporal statistics of those impacts. By including a notion of *energy* in the crumpling process, we can control the time length and the overall dynamics of individual *events*, each one consisting of a collection of "crumples".

The physics-based approach to crumpling-sound reproduction produces a control layer with physical parameters. The advantage of having such parameters at hand is twofold: first, those physical controls can be interfaced with the impact driving parameters directly; second, the user interface presents a consistent control panel to the user, without the need of intermediate maps layered in between the model and the user interface. By means of this design approach we were able to synthesize sounds of *crushing* cans.

Aiming at yet a higher level of scenarios to be modeled, the "user" can be a top-level control structure, which triggers events according to some rule. Rules governing the temporal evolution of *walking* and *running* exist, which are physics-based [10]. Those rules drive the crumpling model parameters directly, in a way that we have obtained interesting walking and running sounds.

Crushing, walking and running are extensively described in an article submitted for these proceedings .

5. FAMILIAR (SOUNDING) OBJECTS

The expressiveness of the sound models is best recognized, when parameters are set to example-values within the wide ranges, that are connected to scenarios familiar from every-day experience. Such demonstrations often envolve combinations of several models; we have chosen some items, partly accompanied with basic visualizations, from rather simple to complex ones:

- The sole impact-model can be tuned to struck bars of different sizes and materials,

- as the low-level friction-model can realize squeaking doors and rubbed glasses.

- The rolling-model with its strong ecological potential (velocity, direction, size ...) sonifies different interactive "games" with rolling balls.

- Rolling and friction are two states of an interactive wheel–brake construction.

- The dropper-object delivers convincing bouncing balls as well as dropping plastic bottles, metallic coins and breaking glasses.

- Natural is the combination of dropping and subsequently rolling balls.

- Typical scenes of crumpling are crushing cans and the sound of walking on gravel.

6. ACKNOWLEDGMENTS

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