Contact Sounds for Continuous Feedback

Davide Rocchesso, Federico Avanzini, Matthias Rath, Roberto Bresin, and Stefania Serafin

***Abstract*— The role of continuous auditory feedback in multimodal embodied interfaces is advocated. Examples of physics-based cartoon sound models (rolling and friction) are used to display deviation from equilibrium and exerted effort in manipulative interfaces.**

I. Introduction

In human-machine interfaces, many tasks (steering, dragging, etc.) require continuous control and continuous feedback. The latter can be acquired visually, kinesthetically, or auditorily, but it is important that in closing the control feedback loop the user does not have to repeatedly change the locus of attention. If the locus is mainly visual, the haptic and auditory channels are both suitable for providing non-distracting, informative feedback.

A particularly interesting arena for experimentation with sounds is that of *embodied interfaces* [1], [2], which often require peculiar control gestures. As an example, selection by tilting can be made more effective if combined with force fields and either haptic or force feedback is provided. The *illusion of substance* [3] lets the user believe that she is manipulating real objects, rather than synthetic artifacts. Somewhat paradoxically, exaggerated effects, such as those used in cartoon animation, can reinforce the illusion of substance and, therefore, the overall degree of embodiment and sense of presence.

Cartoon animation can be applied to GUIs (Graphical User Interfaces), even though it conflicts with the users' need of being in control of object movements. As indicated by Gaver [4] and exploited in the SOb project,[1] sound models can also be cartoonified and used for feedback in GUIs. Sliding or friction sounds can accompany window dragging, and a sudden change of surface texture or friction coefficient can reveal an obstacle or underlying hidden object. Also, constraints such as pinning or snapping can be cartoonified either visually [3] or auditorily (e.g., rolling in force fields).

Indirect manipulation, although often necessary, is problematic as far as feedback is concerned. Michotte [5] showed that motion is responsible for perceived causality, and its use in interfaces and visualization has been proposed [6], [3]. In many cases, continuous sound feedback can emphasize causality as well as the effort being spent in operations.

There are many practical cases where it is desirable to substitute haptic feedback with other modalities (e.g., if one wants to share a sensation of effort with an audience). It was shown [7] that audition is an effective substitute for some typical manipulation tasks. It was also shown that visual feedback can induce the illusion of active force feedback when using a passive control device [8], [9]. Contact sounds have a strong potential in this area, that we are just beginning to explore.

The remainder of the paper discusses various prototypal interfaces where acoustic feedback is generated using real-time physically-based sound models developed within the SOb project, and implemented as plugins to the open source real-time synthesis environment `pd` (Pure Data)[2]. No description is given here of the physical sound models, since all of them have been presented elsewhere (see e.g. [10]). The focus is instead on the use of such contact-sound models (namely, rolling and friction) in multimodal interactive settings.

II. Embodied Interaction

The notion of embodied interaction, as popularized by Paul Dourish [2], relies on the philosophical standpoint that meanings are inextricably present in the actions that people engage in while interacting with objects, with other people, and with the environment in general. As opposed to the cognitive attitude, which is sympathetic with the Cartesian dualism between body and mind, embodied interfaces try to exploit the phenomenological attitude of looking at the direct experience, and let the meanings and structures emerge as experienced phenomena. Embodiment is not a property of artifacts but rather a property of how actions are performed with or through the artifacts. Of course, different designs can elicit different degrees of embodiment, and it is at this level that we intend to operate.

One crucial aspect, we believe, is the fact that human interaction in the world is essentially continuous. Triggers are rare things in nature while, more often, we weigh forces, steer paths, maintain equilibrium. Therefore, it is important to support continuous interaction in interfaces. As an example, consider the task of selecting an item from a list in a portable device. As proposed by Fishkin *et al.* [1], a certain degree of embodiment can be obtained by implementing selection by tilting, in one of the following two ways: (i) letting the list rotate as if tilting introduced a tangential force, or (ii) simulating a ball rolling on a plane where the items are arranged. In both cases we are embedding the list in a force

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[1] SOb – the Sounding Object, EU collaborative R&D project, http://www.soundobject.org

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

Fig. 1. The InvisiBall. Finger position in the 3D space is detected in real-time.

field that we can experience continuously. It is such experience that relies heavily on the quality and nature of displays. It has been proposed [11] that properly designed force fields can be used to ease the access to 2D or 3D widgets when the visual channel is not available or reliable. Force fields can be made audible if translated into sloped surfaces where balls can roll on.

III. ROLLING: FROM THE INVISIBALL TO THE BALLANCER

As part of the Sounding Object project, a convincing sound model of rolling was developed based on a rather sophisticated physical model of impact [10, chapters 8 and 9]. Rolling sounds were considered to be highly significant, as it was previously shown that listeners can discriminate differences in size, speed, and surface texture [12]. In order to demonstrate the use of continuous auditory feedback in interaction we devised an interface called the InvisiBall.

The interface is based on the Max Mathews' Radio Baton [13]. A thimble acts as the sender and the receiving antenna is placed under a 3D elastic surface (see fig. 1). Finger position in the 3D space is detected in real-time and it is used by the algorithm controlling the rolling movement of a ball. By pushing the membrane with the "thimble-sender", users can force the ball to move from rest position in the 3D space and roll towards the finger. The position of the rolling ball as a projection on the XY plane, i.e. as seen from above, is visualized on the computer screen. The position is represented as a colored disk assuming colors in the red-range at high speed (hot ball) and blue-range at low speed (cold ball). In the InvisiBall, the user can rely on three different types of feedback: (i) Acoustic - the sound model of the rolling ball, (ii) Haptic/Kinesthetic - control of the position of the ball by pressing the elastic membrane with a finger, (iii) Visual - graphical projection of position and speed of the ball.

Experiments were performed [10, chapter 12] to assess the degree of realism of this metaphorical/physical interface, under different forms of feedback. It emerged that stimuli were classified as more realistic if only acoustic or acoustic/visual feedback was used (i.e., subjects were not directly controlling the interface). This made us aware of the difficulties of integrating gestural and haptic control with multimodal feedback. In fact, in the InvisiBall there is a mismatch between the physical and geometric properties of the elastic surface that the user is acting on, and the virtual surface that supports the virtual ball movement. Such mismatch determines a disembodiment or, in other words, a decreased sense of presence. Nevertheless, results were promising in indicating the effectiveness of continuous auditory feedback in general, and of the rolling ball metaphor in particular. Therefore, we designed a new interface which offers a more direct coupling (in the sense of [2, pp. 138–144]) between the physical, the virtual, and the actions of the user. Moving from 2D surfaces to 1D lines afforded such transition to the new interface, called the Ballancer.

The metaphor of the Ballancer is very simple: balancing a ball on a tiltable track. The (virtual) ball is free to move along one axis over the length of the track, beeing stopped or bouncing back when reaching the extremities. The acceleration of the ball along the length of the track is directly related to the elevation angle. Possible vertical bounces of the ball or other effects of rotation are neglected, and all the damping experienced by the ball is modeled by one term of friction force, proportional to the instantaneous velocity. The position x of the ball on the track is described by the following differential equation:

$$\ddot{x} = \sin(\alpha) \cdot g - k \cdot \dot{x} \ , \tag{1}$$

where $g = 9.8\text{m/s}^2$ is the gravity acceleration, α is the tilt angle of the track, and k is a damping factor. The physical situation is much simpler than in the InvisiBall, and this simplicity affords both a robust realization and the immediate understanding by naïve users. Another advantage of the Ballancer is that the physical, purely mechanical realization of the metaphor is straightforward. As an example, in our implementation the control track can also hold a real ball moving on its top surface (see fig. 2). In this way the virtual system can be directly compared to its mechanical pendant, to measure how far it is from the "real thing".

Extensive experimentation has been conducted using the Ballancer and it is reported somewhere else [14], [15]. The experiments show that the modeled metaphor is intuitively

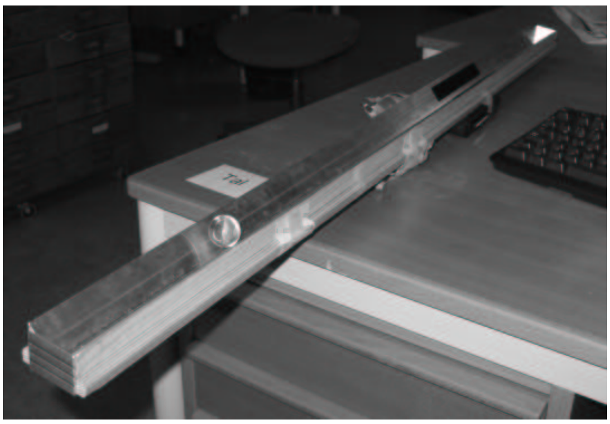

Fig. 2. The "rolling-track" with a glass marble rolling in its upper-face aluminium track.

understood and it can be used reliably, with or without visual feedback. More precisely, they show that: (i) the size of the visual display affects the performance in target reaching tasks; (ii) continuous audio feedback affects the quality of interaction, as the user apparently makes continuous use of velocity information to achieve a more precise behavior.

The combination of modeling everyday sounds and using a familiar control metaphor exhibits the advantage that virtually no explanation and learning are necessary. As opposed to what happens with abstract sounds/controls [16], users may immediately understand and react without being instructed. Moreover, in the case of lacking or poor visual feedback, users make use of information of ball speed, size, and surface texture to drive their control action. The emergence of a mental model is even more clear for the tangible–audible interface than for the actual mechanical device that provides a physical realization of the metaphor. This demonstrates how effective the *cartoonification* [17] approach to sound modeling can be: although the device is perceived as fictitious, nevertheless it can quite reliably elicit an intended mental association, even more clearly than the real thing.

IV. FRICTION: RUBBING, BOWING, SQUEAKING

Together with rolling, friction-produced sounds represent a second relevant category of continuous auditory feedback. As part of the SOb project, a sound model of friction was developed based on a detailed physical description of the frictional interaction between two facing surfaces. The model is derived from [18] and is described in detail in [10, chapter 8]. Such model departs significantly from other physically-based approaches typically used in sound synthesis applications. The main difference is that the model is a *dynamic* one, i.e. the relationship between relative the sliding velocity v and the friction force f is represented through a differential equation rather that a static mapping. As a consequence, the model is able to account for more realistic acoustic transients during non-stationary interaction.

Assuming that friction results from a large number of microscopic elastic bonds (called “bristles” in [18]), the v-to-f relationship is expressed as:

$$f(z, \dot{z}, v, w) = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 v + \sigma_3 w, \qquad (2)$$

where z is the average bristle deflection. The coefficient σ_0 is the bristle stiffness, σ_1 is the bristle damping, and the term $\sigma_2 v$ accounts for linear viscous friction. A fourth component $\sigma_3 w(t)$ relates to surface roughness, w being modeled as fractal noise. This component is needed in order to simulate scraping and sliding effects. The main distinguishing feature of the model is that an additional non-linear first-order differential equation is introduced to describe the average bristle deflection as a function of the sliding velocity. As a consequence, equation (2) is no longer a static v-to-f mapping.

Since many “knobs” are available in the model, a phenomenological description of its parameters has been provided in [10, chapter 8], that can serve as a starting point for the sound designer. In particular, it was found that certain parameters affect overall sound features such as pitch and bandwith, while other parameters are more related to transient effects.

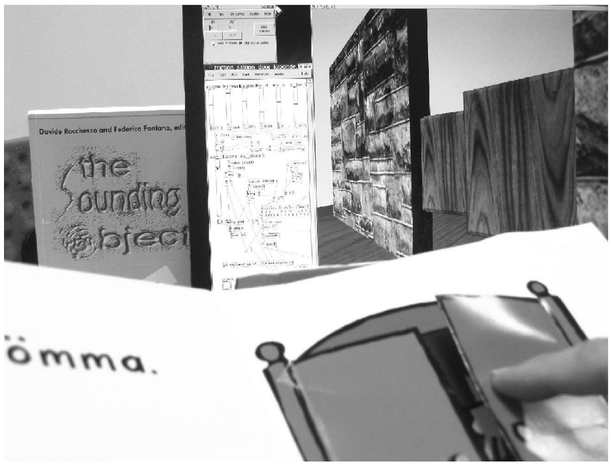

Fig. 3. A tangible audio-visual object: a swinging door in a children pop-up book (bottom) and the corresponding 3D animation (top right).

The friction model has been applied to several examples of acoustic systems with frictional induced vibrations. Among the possible applications, one is the simulation of bowed string musical instruments: a first study in this direction is documented in [19]. Besides musical systems, the model has been applied to the simulation of a variety of complex everyday sounds generated by frictional interactions, which comprise a rolling/braking wheel, a rubbed glass, and a squeaky swinging door, all described in detail in [10, chapter 8]. Audio-visual interactive applications have been generated, where the user controls the external forces acting on a virtual object in the scene through a standard mouse, and the audio (displacement) signals are used to drive both the graphics renderer and the audio feedback. This approach allows for a high degree of interactivity and demonstrates that a single physical synthesis engine can be used for both graphics and audio. One main consequence is that the two modalities are highly consistent and synchronized on a fine scale.

The latter of the above mentioned applications, i.e. a squeaky swinging door, has been used to sonify a tangible object: a swinging door in a children pop-up book. The setup is shown in figure 3. Similarly to the rolling-based interfaces described in the previous section, in this setting the user experiences three types of feedback: (i) Acoustic - the sound model of the squeaking door, (ii) Haptic/Kinesthetic - control of the position of the door by pushing and pulling it, (iii) Visual - animation of a graphical representation of the door.

V. EQUILIBRIUM

It has been shown that continuous auditory feedback can enhance the somatosensory perception of the state of a manipulated object and even provide effective sensory substitution [7] of haptic or visual feedback. We consider equilibrium tasks as possible areas of exploitation of this kind of feedback.

Several complex tasks and interactions can be recast in terms of reaching or keeping an equilibrium point. As an example, selection by tilting [1], [20], already mentioned in

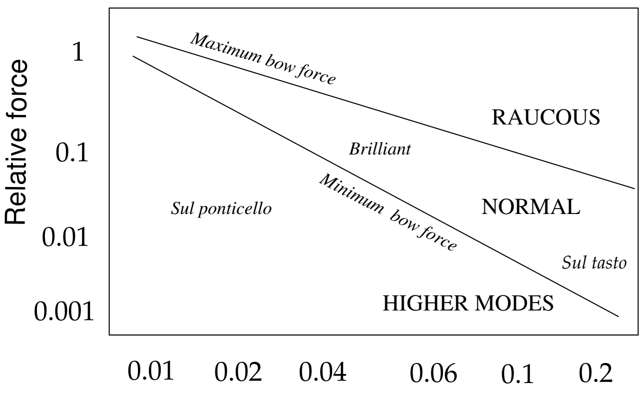

Fig. 4. The original Schelleng diagram, reproduced from [24].

section II, can be reformulated as a task of reaching one among several equilibrium points: a menu can be represented as a horizontal cylinder with a polygonal cross-section; by rotating the cylinder about its axis the user selects different items, and keeps one item selected as the corrisponding face is kept in equilibrium. Feedback is needed to monitor deviations from the equilibrium point, in such a way that the user can operate continuous adjustments to maintain the position. A virtual rolling ball may provide such feedback via visual, auditory, or haptic display. Surface textures can be used to differentiate the items of a menu. By using anisotropic surface textures the metaphor can be extended to 2D, as we may be able to estimate the direction of rolling from auditory or haptic rolling patterns. In this way, we could also provide feedback for 2D selection by tilting, as required in devices such as the Hikari [1] or in some embodied user interfaces [21].

Even the action of steering a path within a corridor, as used in some Fitts-like experiments [22], can be thought of as trying to mantain equilibrium on the ideal middle line. Indeed, any task of steering (e.g., in bicycle riding) can be modeled in differential form as [23]

$$\ddot{\theta} = k(\theta - \theta_0) - b\dot{\theta} \, , \tag{3}$$

which resembles the equation of a damped spring with natural rest length of θ_0. This equation can be readily converted into the equation describing a tilt-and-roll situation (compare with equation (1)). Therefore, auditory feedback via rolling sounds may prove useful for any steering task.

But rolling is just one of the possible metaphors that can be used to provide sonic feedback in equilibrium tasks. Friction is another such metaphor. Indeed, violinists achieve a “balanced” sound by dosing the appropriate amount of bow pressure given a certain transversal bow velocity. When the force increases too much the sound becomes rough, and when the force is too little, a so-called surface sound is produced. This situation is illustrated by the classical “Schelleng diagram” [24] in the force-position plane. The Schelleng diagram was originally formulated to find the playability region of bowed string instruments, i.e. the region of the model parameter space where a “good” tone (as opposed to a raucous tone or tones dominated by higher modes) is achieved.

Figure 4 shows the original Schelleng diagram, which indicates the theoretical minimum and maximum bow force as a function of the relative bow position β along the string. Between the bow-force limits, “Helmholtz motion” is established. Helmholtz motion arises from the stick-slip interaction between bow and string, and is characterized by a single “corner” traveling back and forth on the string under an approximately parabolic envelope. While the corner is between the bow and the nut or finger, the string is sticking to the bow. When the corner is on the shorter part of its journey, between the bow and the bridge, the string is slipping under the bow. A similar diagram can be redrawn in the velocity versus force plane.

Equilibrium in continuous interaction can be reformulated as navigation within the corridor of playability in Schelleng’s plots. This is an example of dynamic equilibrium, as opposed to static equilibrium, since it refers to stationary motion conditions rather than absence of motion.

VI. EFFORT

The display of effort is a crucial aspect of human-machine interfaces, especially for tasks that require continuous manipulation. Many kinds of haptic devices providing force feedback have been proposed and manufactured as a direct solution to this requirement. However, due to the fact that these devices are in most cases cumbersome, expensive, and provide a strictly personal display, a number of alternatives have also been proposed. Sensorial substitution [7] provides the common ground for these alternatives, which include cartoon animation techniques [3], force-feedback simulation via cursor displacement [9], pseudo-haptic feedback [8]. But visual rendering is not necessarily the best surrogate of effort, as in many applications the visual display is too small, too large, or too poor, and dynamic properties of objects are better conveyed by means of sound.

As an exploratory workbench, a 2D interactive animation has been designed which depicts a block sliding on a surface (see figure 5). The animation is intentionally composed of stylized graphical objects, similar to the sketches typically used in psychology for visual experiments [25]. This serves the scope of demonstrating the importance of audio in conveying information when visual cues are ambiguous or very subtle. Audio feedback from the animation is obtained using the friction model described in section IV.

Depending on the applied normal force the block can be either suspended over the surface, as in figure 5(a), or in contact with it, as in figure 5(b,c). As the normal force is increased, the effort required to move the block is increased as well. This is rendered graphically by changing the block color from blue to red and scaling its vertical dimension. Audio feedback obtained through the friction model increases the perception of effort dramatically: the model reacts in a physically consistent way to changes in the normal force, ranging from noisy friction to stick-slip motion, up to chaotic behavior when the normal force reaches extremely high values. The increase of complexity when augmenting the force values is clearly noticeable in the overlaid spectra of figures 5(b,c).

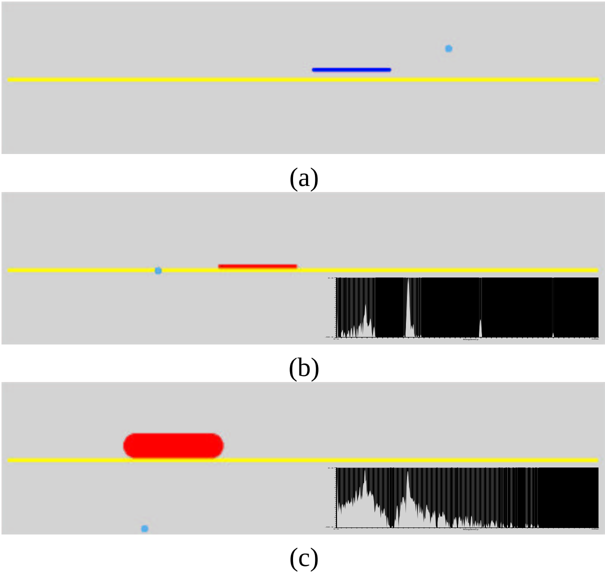

Fig. 5. A 2D animation of a block moving on a surface. Audio feedback from the friction model elicits perception of effort. The blue dot indicates the position of the "handle" (mouse) which pulls the block. Spectra of two audio frames are overlaid to the corresponding image frames.

An example of visual perception of effort is found in the braking effect studied by Minguzzi [26, pp. 300–301]. His 2D visual experimental setup comprises a disk which moves with constant velocity until it crosses a colored strip. The disk velocity exhibits an abrupt slow-down during the crossing and recovers completely at the exit from the strip. Perceptual experiments have shown that subjects tend to describe the situation as the disk being blocked by the colored strip, which is then perceived as a viscous surface.

The situation is similar to what was found in a game application of the Ballancer, where the player has to move the ball to a specific target (portion of the track). Such target is characterized by a different surface texture that increases motion damping. When the ball enters the target area there is a clear change in sound quality that immediately conveys a sense of increased damping. Conversely, changes in visual motion due to such damping are much subtler and difficult to capture.

VII. Conclusion

We have advocated the use of continuous auditory feedback in embodied interfaces. Physics-based sound models can afford immediate and accurate grasping of phenomena such as equilibrium or effort.

In many cases, a degree of "cartoonification" has to be applied to sound models to make them sharper and less ambiguous. Rolling and friction sound models are being used in new interfaces, and their effectiveness in multimodal contexts is being investigated.

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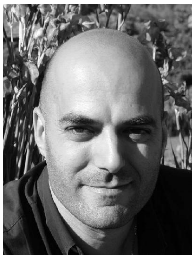

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