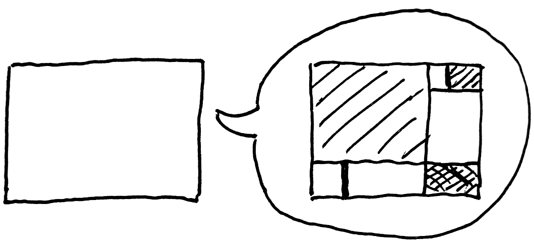
Exposé zur Dissertation

Perceptual Plausibility in Augmented Auditory Feedback for Interaction with Physical Objects



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June 17, 2017

Abstract

In our physical world, interactions with physical objects usually evoke sounds. This auditory feedback depends on the involved objects and the specific type of interaction. For Human Computer Interaction (HCI) applications, it could be beneficial to provide "augmented" auditory feedback, e.g., in order to better communicate certain object- or interaction-specific characteristics. Further, the communication channel which is gained by modulating the original auditory feedback can be used for ambient sonification of completely unrelated external data. It is hypothesized that physical modeling sound synthesis is well-suited for this kind of auditory augmentation, as model parameters can be changed in real time while creating realistic and lively sonic results. An open question is the resolution of the achieved information channel within the range of perceptual plausibility of the augmented auditory feedback. Further, the possibilities of auditory augmentation for artistic purposes are explored, such as for computer music or interactive sound installations.

Zusammenfassung

In unserer physikalischen Welt werden durch Interaktionen mit physikalischen Objekten überlicherweise Klänge hervorgerufen. Dieses akustische Feedback hängt sowohl von den beteiligten Objekten, als auch von der Art der Interaktion ab. Besonders Interaktionsdesign bzw. auditorische Displays könnten von einem ërweitertenäukustischen Feedback profitieren, z.B. um bestimmte Objekt- oder Interaktions-spezifische Charakteristika besser mitzuteilen. Weiters kann der Informationskanal, welcher durch Modulation des ursprünglichen akustischen Feedbacks gewonnen wurde, zur Sonifkation beliebiger externer Daten genutzt werden. Es wird angenommen, dass eine Klangsynthese mittels physikalischer Modellierung für die angedachte Anwendung gut geeignet ist, da hierdurch realistische und lebendige Klangergebnisse erzielt werden können, während Modellparameter in Echtzeit veränderbar sind. Hierbei stellt sich die Frage, welche Auflösung mit dem gewonnenen Informationskanal möglich ist. Eine Einschränkung hierfür ist die perzeptive Plausibilität des erweiterten akustischen Feedbacks. Untersucht werden soll außerdem, welche künstlerischen Möglichkeiten durch erweitertes akustisches Feedback eröffnet werden, beispielsweise für Computermusik oder interaktive Klanginstallationen.

Physical interaction and auditory feedback

Figure 1: Physical interaction and auditory feedback.

As we live in a physical space, we interact with other physical objects, such as a table, the floor we are walking on, or objects we take in our hands. Such physical interactions[1] usually evoke specific sounds, depending on the physical properties of the involved objects, such as material, shape, or size, and also depending on the type of interaction, i.e., excitation (scratching, hitting, etc.). As these sounds can be seen as a reaction on a preceding (physical) action, they are referred to as auditory feedback. In combination, auditory feedback represents a major part of our everyday acoustic environment which we use either consciously or unconsciously while pursuing our activities. In the domain of Human Computer Interaction (HCI), we refer to activity theory[Kuu95; Kap95] to distinguish between (conscious) actions and (unconscious) operations (behavior). A possible action could be, for example, shaking a box in order to get information on its contents from the resulting sound. Our operations are influenced by auditory feedback as well, for example, through footstep sounds which reveal important information on the material of the ground and thus (unconsciously) influence our walking style [Bre+10; MES15; PF12; TB15].

In general, auditory feedback does not appear alone (unimodal) but is usually accompanied by feedback in other sensory modalities, such as vision and haptics. Only those three modalities are considered in the context of this research. Haptic feedback is used as an umbrella term for haptic, tactile, and kinesthetic feedback.

Auditory augmentation

Although auditory information usually gets combined with input from other channels, such as visual or sensory information, it is always desired to get as much data as possible from all individual channels. For Human Computer Interaction (HCI) applications it would be beneficial to generate auditory feedback which somehow exaggerates/augments the real physical sound in order to convey more relevant information (or remove irrelevant parts).

In movies, for example, it is common practice to use "hyper-realistic" sounds which are exaggerated artificially to better communicate certain important aspects. While such exaggerated sounds may appear unnatural or artificial when played back in isolation, the over-exaggeration could even lead to a more natural impression when put in the right context.
This technique of handling realistic sounds in a way that are somehow exaggerated or excessive has also found its way into electroacoustic music [Cre05].

[1] The focus at this juncture is on physical interaction, in contrast to, e.g., social interaction.

Such exaggerated auditory feedback is supposed to provide improved signal-to-noise-ratio compared to the unprocessed sound. This could improve interaction with physical objects in two ways:

Firstly, it could help communicating object properties, such as material or spatial dimensions. In controlled experiments, it was shown that physical plates of identical surface area but different shape can be discriminated by sound alone [KT00]; however, the plates were always heard smaller than they actually were. Different materials modulated the perceived spatial extent. The perceived spatial extent of wooden rods was found to be somehow compressed, meaning long rods were perceived shorter, while short rods were perceived longer than they actually were [CAK98].
Gross material categories (steel/glass vs. wood/plexiglass) can be distinguished perfectly by their striking sound, while in-category identification is strongly influenced by interpretations based on the everyday acoustic environment [GM06]. In particular, glass and wood were associated with smaller objects than metal and plastic.

Further, the the sonic result of the specific interaction type could be augmented as well, for example to facilitate a specific action.
It has been shown that contact sounds have an impact on our behavior when interacting with physical objects: Augmented footstep sounds are able to influence the perception of vibrotactile cues underfoot and the gait cycle [PF12].

Finally, the newly created communication channel can be used for sonification of completely unrelated data, e.g., for continuous sonification of background task information. For this sonification approach, [BTH10] introduced the term "auditory augmentation". They presented a system which transforms (augments) the original physical auditory feedback, depending on real-time external data, in order to convey information (see Fig. 2). The input signal from a vibration sensor which is attached to the physical object is processed by a digital filter whose parameters are controlled by the external data. The final signal is then rendered by loudspeakers and blends with the object's original sound, providing an additional layer between people's action and an object's auditory feedback. The authors successfully used this approach in a peripheral monitoring situation. The concept of auditory augmentation is strongly connected to blended sonifications, which "blend into the users' environment without confronting users with any explicitly perceived technology" and thus provide ambient sonification channels [THH13].

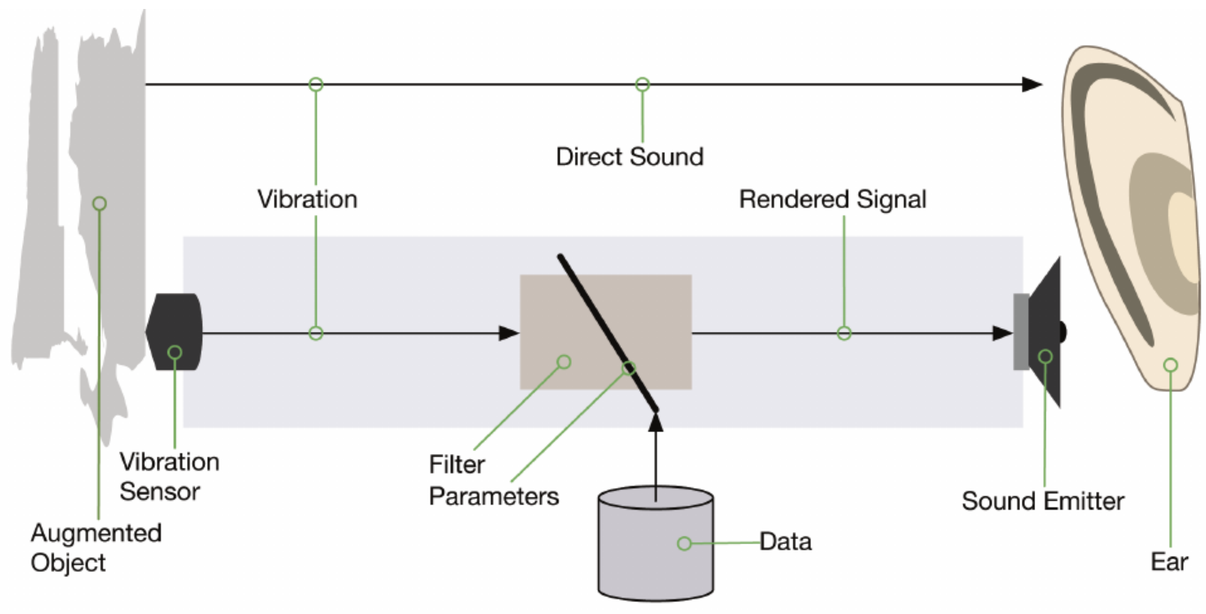

Figure 2: General model of auditory augmentation [BTH10].

While there have also been efforts to provide auditory feedback for gestures (i.e. body movements without interaction with a physical object), e.g., [Fra+16], this case is only marginally relevant from the perspective of auditory augmentation. However, an interesting aspect is the special case of interaction with virtual objects, without haptic or visual feedback. [Fur+15] evaluated the effect of auditory feedback by tapping on a virtual surface. Tapping sounds of low level led to significantly higher physiological arousal than of tapping sounds of high level.

Some studies concerning augmented feedback (visual, auditory, haptic, or multimodal) concentrate on motor learning. [Sig+13] gives an overview of its potential and challenges and provides design criteria to successful visual, auditory, haptic, and multimodal feedback. In general, auditory feedback has a positive influence on the task performance. It has been shown that auditory feedback does not improve typing performance on a computer keyboard if additional haptic feedback is present; in the unimodal case, haptic feedback has stronger influence than auditory feedback [Ma+15].

Plausibility

Sensory feedback is considered to be plausible if it is "conceptually consistent with what is known to have occurred in the past" [CK06]. In particular: "A highly plausible scenario is one that fits prior knowledge well: with many different sources of corroboration, without complexity of explanation, and with minimal conjecture" [CK06].

It is therefore hypothesized that the perceptual plausibility increases with increasing congruency (agreement) between cues (information) from different sensory modalities (information channels): a tiny object producing a loud sound at low frequency does not fit the acquired knowledge of everyday sounds and therefore might be judged as being implausible.

With growing strength of auditory augmentation, the resulting auditory feedback influences user perception, emotion, and behavior [Fur+15]. Auditory cues have been shown to influence the haptic perception of virtual textures presented by the Phantom Omni[2] haptic device [Ser+07]. Also [Mar+15] concluded that material quality perception (e.g. hard/soft, rough/smooth) is strongly influenced by auditory cues. If the transformed feedback differs too much from the original physical feedback, it gets implausible. As the perceptual plausibility is dependent on the congruency between different modalities, such as haptic, visual, or auditory information, it has no meaning for the unimodal case of auditory feedback alone. Perceptual congruency and therefore plausibility is given if the information of the different modalities combined, i.e., the combination of different stimuli, matches the pattern we learned through natural interactions with our physical environment. While multimodal perception could also include olfactory or gustatory qualities, this research concentrates only on auditory, visual, and haptic cues.

Perceptual plausibility is also affected by contextual information. The information from auditory, visual, and tactile feedback can be perfectly congruent between each other, but still incongruent to contextual information. Consider a person who is looking in another direction while putting a glass on a table: The auditory-haptic feedback from a table of 20 m length might be perfectly plausible in the dining hall of a castle, but could become implausible in the average apartment. A specific plausibility is therefore only valid under specific environmental conditions.

It must be considered that people are already accustomed to "fake" visual feedback, but are usually not accustomed to "fake" auditory or tactile feedback. It is common knowledge that

[2] Phantom Omni haptic device: `http://www.dentsable.com/haptic-phantom-omni.htm`

a physical object's properties can be concealed, e.g., through painted surfaces. Therefore, the vision modality might be more robust to incongruence than both other modalities. However, according to [CK06], this would still lead to a more complex explanation and a higher conjecture, which both lead to a decrease in plausibility.

Usability

In addition to the described object- and environment-dependent plausibility range, the human activities which affect the observed object must be considered: The usability of an object should not be deteriorated by altered sensory feedback. It is hypothesized that the usability in this context depends on the following two conditions:

1. the extent to which the task-relevant physical properties of the affected objects are conveyed acoustically, and
2. the extent to which these perceived properties fit the physical objects' real properties.

These conditions can be evaluated experimentally with test participants judging physical objects' properties on scales, e.g., as described in [Mar+15].

A measure for the first condition is then provided by the Inter-Participant Correlation (IPC) [Mar+15]: "if a property is clearly transported by a certain stimulus, the participants should generally agree on the judgment of this quality. Contrary, if the information is not well depicted by the presentation, the participants will have tu use their imagination for rating and thus are expected to agree less."

[Mar+15] also provide a hint for the second condition: "We consider a certain material presentation to be well-suited to represent a certain property if participants rate close to the full-modal presentation. Contrary, when the ratings are far apart, the presentation is judged to be less realistic and thus less suitable". In our case, we therefore consider the augmented auditory feedback to be usable if the ratings of relevant properties are close to the ratings of the original (not augmented) condition. On the contrary, ratings which are significantly different from the original condition indicate an altered perception of the object – as a consequence, this could lead to deteriorated usability.

As the relevant physical properties might be different for different tasks, it is necessary to discuss the observed object's purpose and what kinds of activities affect it. In the first step, a rather simple object category is chosen – a horizontal, even, rigid, and stationary surface. Such a surface usually appears on tables, cupboards, bookshelves, etc. Due to their "affordances" [Nor02], the mentioned objects are primarily used for putting things on top of them and moving these things around. The ground is not considered in this experiment, as it adds additional affordances, such as walking.

Not all physical properties of the observed object (surface) are relevant for the task of putting things on top (the term "things" is used for objects which can be put onto the surface to avoid ambiguities). A logical consequence is that relevant properties must be conveyed by sensory feedback without modification in order to facilitate all possible tasks within the object's purpose. Physical properties which are irrelevant for accomplishing a specific task, i.e., irrelevant for the usability, might be possible candidates for auditory augmentation. Only object properties which are at least partly conveyed in the acoustic domain are considered, as it is assumed that all other properties (e.g., purely visual properties such as color, etc.) are not affected by auditory feedback.

Concerning the observed rigid surface, properties which are assumed to be relevant for usability include:

- *hardness*: hard surfaces, e.g., concrete, might be more "dangerous" for fragile things than, e.g., wooden surfaces.
- *roughness*: the roughness influences how objects can be moved on the surface.
- *sturdyness*: a fragile table might break by putting heavy things on it.
- (*temperature*: a hot surface might hurt. However, this property is not conveyed acoustically.)

Properties which are assumed to be irrelevant for accomplishing the task of putting things onto the surface include:

- *size*: the size of a table does not affect how things are put on top of it.
- *shape*: the shape of a table might have an influence at a social and psychological level; however, it is assumed that this influence comes from the spatial distribution of persons and not from the sensory feedback provided by the table itself.
- *volume*: the thickness of the tabletop is assumed to have no influence on its purpose.
- *hollowness*: it does not matter if the tabletop is solid or hollow, if it remains sturdy.
- *weight*: the object is assumed to be stationary and therefore never moved.

The latter properties are assumed to be irrelevant for usability and may be securely altered (augmented) within their individual object- and environment-specific range of plausibility.

It must be noted that by now, we only considered the conveyance of information on the observed object and we excluded information on the performed action. However, [LH12] showed that action identification is generally quite robust and not altered significantly by the material of the involved objects.

Behavior change

Augmented auditory feedback can also have an effect on the user behavior, i.e., the way how a specific task is performed. If the augmentation lowers the performance of a task within the scope of the object's purpose, the usability is assumed to be deteriorated. However, if an auditory augmentation is capable of inducing such a behavior change this augmentation is assumed to be highly plausible.

Goals of augmented auditory feedback

Three different goals of augmented auditory feedback emerge at this point.

1. Systematic auditory augmentation to force a specific behavior change, e.g., make people place their wine glasses on the table more carefully. This leads to the following questions:
    (a) How can noticeable auditory augmentation help to induce a certain change in behavior?
    (b) How can such a behavior change be measured?

2. Plausible auditory augmentation which is noticed by the users (and therefore could be exploited for conveying information) but which does not deteriorate the object's usability. This leads to the following questions:
   (a) How can noticeable auditory augmentation be applied in order to not induce any change in behavior?
   (b) How could such an unwanted behavior change be measured?
   (c) How could the effectiveness/accuracy of the conveyed data be measured?
3. Auditory augmentation for explorative data analysis. The object is used as medium for the exploration of arbitrary data, e.g., through scratching, hitting, etc. This implicates a transformation of the object's original purpose. This leads to the following questions:
   (a) How can auditory augmentation be applied in order to not induce any change in behavior?
   (b) How could such an unwanted behavior change be measured?
   (c) How could the effectiveness/accuracy of the conveyed data be measured?

All three goals require a certain amount of perceptual plausibility in the augmented auditory feedback. The goals might be compatible to some extent and could be used in combination. However, in an experiment, they need to be examined in different ways.

Synthesis of auditory feedback

Most human interaction with physical objects involves hands and feet and includes actions such as hitting, scratching or grabbing. In order to provide realistic sounding, i.e., plausible, auditory feedback for such interactions, the sound synthesis is supposed to be based on physical models of the involved physical objects and their interaction. Physical modeling sound synthesis is seen as being most suitable for this purpose. While traditionally used for realistic reproduction of the sonic behavior of physical objects, such as musical instruments, this method opens the possibility to systematically tune specific physical properties while still retaining a natural sound characteristic.

In audiovisual renderings, such as computer games or animated movies, it is already quite common to use the same rigid-body 3D models for computer graphics and physical modeling sound synthesis in order to create realistic interaction sounds [Bru06; OSG02]. While [Bru06; OSG02] used an especially efficient modal synthesis approach, more flexibility could be achieved with 2D or 3D digital waveguide meshes [VS93] or lumped mass networks.

Within the "sounding object" project[3] [RF03] various methods for real-time control of object properties have been proposed (e.g. [AR01]) as well as different interaction types (e.g. contact sounds [RRA02], rubbing [ARR02; ASR05], and rolling interaction [Rat03]. A more recent synthesis approach for continuous-interaction sounds (rubbing, scratching, rolling) was proposed by [Con+14].
An elaborate system for generating realistic auditory feedback of footsteps was presented by [Léc+11].

In the general case, however, the natural auditory feedback is always present and cannot be neglected. The synthesized sound mixes with the original sound and auditory augmentation

[3] The sounding object: http://www.soundobject.org/

can only be achieved as an addition to the natural auditory feedback. Both original and augmented sound must mix smoothly in order to be perceived as one single auditory object. This means, there must be a specific level of correlation between natural and synthesized sound. Especially if the sound synthesis is based on a physical model, this smooth mix could be a difficult task. However, if the excitation signal is provided by vibration sensors such as piezoelectric microphones, the physical model can be seen as a filter whose output is highly correlated with the original auditory feedback. This leads to the additional problem that the excitation signal already includes the response of the physical object. In order to use such a signal as excitation of the physical model, it may be necessary to cancel the influence of the resonant object. This can be seen as an inverse filtering problem. While this task could be hard to accomplish, it may be possible to achieve acceptable results with only rough approximation and simple data conditioning steps.

Methodology

First of all, an extensive literature review on all the discussed topics is planned. Based on the results, the first milestones are formulated in order to begin with the implementation.
Based on the specific objectives, solutions for the main parts of a prototyping system will be chosen. These include:

- Sensing hardware (e.g. contact sensors or optical tracking)
- Control data processing (localization of interaction points, interaction type identification)
- Sound processing (physical modeling of object and interaction)
- Spatial sound projection (sound spatialization and rendering with loudspeakers or headphones)

A very basic prototyping system could be based on a touchscreen device or tablet. Due to the small size, spatial sound projection can be neglected and physical interaction is limited to tapping and scratching.

Hardware platform: The BeagleBone Black[4] with the Bela[5] audio cape, designed for sub-millisecond-latency audio and sensor processing [MZ15] and targeting specifically for digital musical instruments [Z+14]. The Bela platform is based on Xenomai[6] Linux and can load code in C/C++, Pure Data, or Faust.

Especially relevant for the sensing hardware and computational complexity, the delay of the augmented auditory feedback must lie below a certain threshold in order to be successfully combined with visual or haptic information. Typical maximum thresholds for synchronous perception are at 25 ms for auditory-tactile delay [Alt12] and 18–42 ms [Ade+03; Lev+00] for audio-visual delay. However, for trained users, such as musicians, [Alt12] recommends a latency below 10 ms.

It is planned to implement a software which is able to load arbitrary 3D models, e.g., as a text file in the open Wavefront OBJ standard. The file contains a finite elements representation of the physical object (e.g. positions of masses and links between them), and can be easily extended by additional information such as material properties. If needed, the interacting

[4]BeagleBone Black: `https://beagleboard.org/black`
[5]Bela audio cape: `http://bela.io/`
[6]Xenomai Linux: `https://xenomai.org/`

object (e.g. hand tool) is loaded as a 3D model as well. These models are then used for the sound synthesis.

The sound processing must be done in real time to be able to change critical parameters continuously at any time. Such parameters could be damping or stiffness, both connected to the object material. Furthermore, the model(s) of the object(s) could be scaled in size. Also the interaction type and corresponding parameters could be changed (e.g. pressure or speed). Finally, additional components could be added to the model, such as new spatial dimensions. By spatially expanding a three-dimensional model in a fourth dimension, it could be enlarged while still maintaining its specific three-dimensional shape. However, such increased dimensionality could introduce unwanted problems for wave propagation [Bal04a; Bal04b]. Another aspect which should be examined is the introduction of additional nonlinearities into the model.

The proposed work aims at answering the following central research questions:

- In what ways can physical models be altered for augmented auditory feedback?
- What are the limitations of auditory augmentation in order to retain plausible interaction?
- What resolution is possible for the added information channel within the range of plausibility?
- How can auditory augmentation help communicating object characteristics, such as material or shape?
- What possibilities are opened from an artistic point of view?
  - For (virtual) musical instruments: e.g. modulating the sound by external data, while retaining plausible interaction for the player.
  - For interactive sound installations: e.g. "self-explaining" functionality without prior knowledge due to the direct connection to the physical world.

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