Applied Acoustics 83 (2014) 22–31

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Custom made wireless systems for interactive footstep sounds synthesis

Luca Turchet *

Department of Architecture, Design and Media Technology, Aalborg University Copenhagen, A.C. Meyers Vænge 15, 2450 Copenhagen, Denmark

ARTICLE INFO

Article history:
Received 30 August 2013
Received in revised form 6 March 2014
Accepted 10 March 2014
Available online 12 April 2014

Keywords:
Interactive sonification
Locomotion interface
Physical modeling

ABSTRACT

This paper describes both the hardware and software development of three custom made wireless systems used for the interactive synthesis of footstep sounds. The data collected from the detection of the feet movements of a walker are used for real-time control of physical models for the auditory display of different ground textures and shoe types. The first system is based on a wooden plank under which an array of microphones is placed. The second system exploits the motion capture technology. The third system consists of a pair of sandals enhanced with two force sensitive resistors and two 3-axes accelerometers for each shoe. The characteristics of the three architectures are discussed and compared. The developed locomotion interfaces find application in several contexts, such as augmented reality, virtual reality, or entertainment, as well as in perceptual studies investigating the influence of interactive sounds on locomotion performance usable for training and rehabilitation purposes.

1. Introduction

Sonic interaction design is a research area which explores methods to convey information (also in terms of aesthetic and emotional qualities) by means of sounds in interactive contexts [1,2]. On the one hand, this research field addresses the challenges of creating interactions mediated by the sound by means of designing and implementing novel interfaces to control sonic events as response to the gestures of one or more users. On the other hand, it investigates the action-perception loop deriving from the interaction with the developed interfaces. The user actively manipulating the designed sonic interfaces discovers how his/her actions modulate the sound. In addition, the auditory feedback can in turn guide the actions of the user by providing the information about how to modify the actions themselves.

Sonic interaction design is closely connected with a subtopic of the human–computer interaction field termed sonification [3]. Such a research field addresses how information can be conveyed in an auditory, typically non-speech, form. Basically, data of various nature are transformed into sound so that the listener is supported to better understand and interpret them. The study of the human interaction with a system that transforms data into sound is a subfield of sonification called interactive sonification [2].

A related concept important to the design of interfaces for human–computer interaction, and particularly significant for sound-based communication purposes, is that of embodied interaction. It has been defined by Dourish as "*the creation, manipulation and sharing of meaning through engaged interaction with artefacts*" [4]. According to Dourish meanings are necessarily present in the actions that people accomplish during the interaction with objects, with other people, and with the environment. As a consequence, perception and action are linked. Embodied interactions occur in real-time and real-space as a part of the world in which we are situated. As a result of this view, the so-called embodied interfaces allow for direct manipulation and are based on a closed loop paradigm where the control of the interfaces is exerted by the user via a continuous and simultaneous set of gestures and perceptions.

A specific case of interactive sonification regards the interactive transformation of actions into sounds. Object of the present work is the interactive sonification of a walker's feet movements tracked by different types of wireless locomotion interfaces. Lately, the interest towards the development of locomotion interfaces capable to provide real-time auditory feedback to the walker is noticeably growing [5]. This is also due to the wide range of scenarios in which such interfaces find application. In virtual reality contexts, augmented floors [6,7] have been developed to provide the user with footstep sounds while physically navigating in the virtual environments. In training and rehabilitation contexts, instrumented insole systems have been built to present corrective information to the patient by means of auditory feedback [8,9]. In interactive art, especially dance, shoes enhanced with sensors have also been developed [10,11]. On a different vein, the attention of researchers has been devoted to the creation of shoes for real-time gait analysis [12–14]. Requirements in the various situations are

* Tel.: +45 9940 2498.
E-mail address: tur@create.aau.dk

http://dx.doi.org/10.1016/j.apacoust.2014.03.005

obviously quite different. While in gait analysis research accuracy of the system is the most important factor, in interactive arts and virtual reality applications the main design parameter is timeliness: a system with a considerable latency is evaluated as unusable in any real-time multimedia application.

On the other hand, most of the research efforts on the synthesis of footstep sounds have been focused on algorithmic solutions not suitable for a direct parametric control during the act of walking [15–18]. A noticeable exception is the sound synthesis engine proposed in [7], capable to interactively sonify foot movements into footstep sounds on various types of surface materials. Recently that work has been extended, allowing the simulation of various types of shoes and the modeling of some anthropomorphic features such as gender and weight of the walker [19]. Such an engine was based on physical models which were driven by an exciter signal expressing the type of foot–floor interaction (e.g., walking, running, sliding, jumping). Various systems for the generation of such an input in real-time with the walker's foot movements were developed and tested [7,20–24].

One of these systems consisted of microphones, placed on the floor at the corners of a square configuration, that detected the footstep sounds generated by a user [7]. Subsequently, the captured signal was provided as input to the synthesis engine, in order to simulate footstep sounds on materials different from the one the user was walking on. This apparatus allowed to reach the requisite of shoe independence and it was very accurate in the detection of the user's feet movements. However, the user was required to navigate in a specific location delimited by the space inside the microphones. Furthermore, this method required that the environment was quiet, since the microphones had to capture only the user footstep sounds, and any other signal constituted a not negligible input error for the footstep synthesizer. This means that the sound could not be delivered to the user through loudspeakers but it had to be conveyed through headphones.

A similar architecture based on a set of accelerometers was also proposed in [7]. The accelerometers were attached to a board where the users could walk upon, with the goal of capturing the signal propagated through the board and thus obtaining an audio range signal expressing the foot–surface interaction. This system presented the same limitations of the microphones-based system with in addition the problem of a lower level of accuracy in the detection of the footsteps dynamics.

Another system that was proposed consisted of shoes enhanced with pressure sensors, which triggered the footstep sounds according to the steps of a user [20]. Such an approach was not shoe-independent and made use of wires connected to the shoes, with the disadvantage of preventing a completely free navigation. More importantly, it did not take into account the exact step movement made by the user, therefore the resulting auditory feedback suffered a lack of realism. In addition, it was not possible to detect when the user was sliding the foot on the floor since the pressure sensors alone were not enough to serve this purpose. Such a system was preliminarily evaluated with user experiments reported in [24]. Results showed that users judged the interaction with the system not too much natural and that they felt quite constrained during the act of walking. Users reported that the main cause for these results was the presence of the wires.

Starting from the architectures proposed in previous research, as well as from the experimental results achieved with the testing of those solutions, three novel wireless interfaces have been developed to advance the state of the art in the research on interactive sonification of a walker's feet movements. The focus in the design of such interface was to provide the walker with stimuli valid from the ecological point of view [25–27]. To achieve such a goal, three requirements were set in the design of the three prototypes: (i) real-time control of the footstep sounds synthesizer; (ii) accuracy of the feet movements detection in order to achieve a wide range of dynamics in the produced sounds; (iii) freedom of navigation when interacting with the systems; and (iv) embodiment of the interaction.

2. Synthesis of footstep sounds

The utilized sound synthesis technique was based on considering a footstep sound as the result of multiple micro-impact sounds between the shoe and the floor. The set of such micro-events was considered as a high level model of impact between an exciter (the shoe) and a resonator (the floor). The synthesis of a footstep sound on different kinds of materials was achieved starting from a signal in the audio domain containing a generic footstep sound on an arbitrary material. It consisted in removing the contribution of the resonator, keeping the exciter and considering the latter as input for a new resonator which implements different kinds of floors. Subsequently the contribution of the shoe and of the new floor were summed in order to have a complete footstep sound.

In [28] the problem of extrapolating the exciter from the acoustic waveform of a footstep sound was addressed. The results of such research led to the conclusion that an optimal solution to obtain such an exciter consisted of extracting its amplitude envelope. The envelope (e) was extracted from the signal (x) by means of the non-linear low-pass filter proposed in [29] and subsequently utilized in [15]:

$$e(n) = (1 - b(n))|x(n)| + b(n)e(n-1)$$
$$\text{where} \quad b = \begin{cases} b_{up} & \text{if } |x(n)| > e(n-1) \\ b_{down} & \text{otherwise} \end{cases}$$

where n and $n-1$ indicate respectively the current and previous sample (sample rate 44,100 Hz) of the discretized variable they refer to, and b_{up} and b_{down} are equal to 0.8 and 0.995 respectively. Fig. 1 shows both the waveform and the corresponding envelope of a typical footstep sound on a concrete floor as well as the sound resulting from the sliding of the foot on the same floor.

In order to simulate the footstep sounds on different types of materials, the envelope extracted with this technique was used to control various sound synthesis algorithms based on physical models. Specifically, the involved sound models were those described in [30,31] for impacts, in [32] for frictions, in [33] for crumpling events, in [15] for particles interactions (PhISM), and in [19] for solid–liquid interactions. By using such models either alone or in combination with each other, the simulation of a large palette of footstep sounds on solid (e.g., wood), liquid (e.g., puddles), and aggregate surfaces (e.g., gravel) was achieved.

On the other hand, various types of shoes were simulated by using different types of exciter signals along with an appropriate tuning of the parameters controlling the involved sound models. For a detailed description of the above mentioned approaches the reader is referred to [7,19]. The proposed footsteps synthesizer was implemented in the Max/MSP sound synthesis and multimedia real-time platform.

3. Microphones-based system

This section describes a non-intrusive shoe-independent system conceived as evolution of the architecture involving four microphones mentioned in Section 1. Such a system consisted of a wooden plank (5.40 m long, 90 cm wide and 7 cm tall, under which a set of nine microphones was placed to detect the feet–floor interaction (see Fig. 2(b)). The microphones (Line Audio Design CM3) were arranged on the floor at an equal distance of 60 cm from each other along the line lying at the half of the plank width. In particular, each microphone was attached to the floor by