Audio-haptic physically-based simulation of walking on different grounds

Turchet, Luca; Nordahl, Rolf; Serafin, Stefania; Berrezag, Amir; Dimitrov, Smilen; hayward, Vincent

Published in:
Proceedings IEEE Multimedia Signal Processing Conference

DOI (link to publication from Publisher):
10.1109/MMSP.2010.5662031

Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

Proc. of MMSP'10 2010 IEEE International Worshop on Multimedia Signal Processing, Oct 4-6, 2010, Saint Malo, France, pp. 269-273

Audio-haptic physically-based simulation of walking on different grounds

Luca Turchet #1, Rolf Nordahl #4, Stefania Serafin #2, Amir Berrezag *6, Smilen Dimitrov #3, Vincent Hayward *5

Aalborg University Copenhagen, Medialogy
Lautrupvang 15, 2750 Ballerup, Denmark
1 tur, 2 sts, 3 sd, 4 rn@media.aau.dk

* UPMC *Univ Paris 06, Institut des Systèmes Intelligents et de Robotique*
4 place Jussieu, 75005 Paris, France
5 vincent.hayward, 6 amir.berrezag@isir.upmc.fr

***Abstract*—We describe a system which simulates in real-time the auditory and haptic sensations of walking on different surfaces. The system is based on a pair of sandals enhanced with pressure sensors and actuators. The pressure sensors detect the interaction force during walking, and control several physically based synthesis algorithms, which drive both the auditory and haptic feedback. The different hardware and software components of the system are described, together with possible uses and possibilities for improvements in future design iterations.**

I. Introduction

In the development of multimodal environments such as games and virtual reality installations, walking sounds are often used to produce physicality and a sense of action, with the overall goal of heightening the realism of a character or person. Such sounds are usually obtained from sound libraries or recorded by *Foley* artists, who often wear shoes in their hands and interact with different materials to simulate the act of walking on different surfaces. Such process is rather time-consuming, and can nowadays be complemented by approaches which take advantage of the developments of technology. As a matter of fact, recently the production of walking sounds has been approached algorithmically, and several solutions have been proposed to simulate the sounds produced during the interaction between a foot and a surface. One of the pioneers in this direction is Perry Cook, who proposed a collection of physically informed stochastic models (PhiSM), which simulate several everyday sonic events [4]. Among such algorithms the sounds of people walking on different surfaces were simulated [5]. A similar algorithm was also proposed in [9], where physically informed models simulate several stochastic surfaces. Procedural sound synthesis of walking has also been recently described in [8].

To our knowledge, the topic of audio-haptic simulation of the act of walking has not been investigated yet. However, lately the interest in investigating the interaction between touch and audition has grown. The possibility of investigating the interaction between auditory and haptic feedback has been facilitated by the rapid progress of haptic technology, together with the development of efficient and accurate simulation algorithms. Several studies have indeed investigated the multimodal recognition of textures [13] and stiffness, both using recorded stimuli [6] and simulations based on physical models [1].

The cited studies have focused on the interaction between touch and audition in hand based interactions. On the other hand, the interaction of auditory and haptic feedback in foot has not been studied, except by Giordano et al., who showed that the feet were also effective at probing the world with discriminative touch, with and without access to auditory information. Their results suggested that integration of foot-haptic and auditory information does follow simple integration rules [11].

In previous research, we described a system able to simulate the auditory and haptic sensation of walking on different materials and presented the results of a preliminary surface recognition experiment [14]. This experiment was conducted under three different conditions: auditory feedback, haptic feedback, and both.

By presenting the stimuli to the participants passively sitting in a chair, we introduced a high degree of control on the stimulation. However, this method of delivery is highly contrived since it eliminates the tight sensorimotor coupling that is natural during walking and foot interaction. It is true for the auditory channel, but even more so for the haptic channel. In spite of these drastically constrained conditions, performance was surprisingly good.

In this paper, we extend the developed technology by allowing subjects to walk in a controlled laboratory, where their steps are tracked and used to drive the simulation. We believe that introducing a higher level of interactivity significantly enhances the perceived quality and realism of the simulation.

The results presented in this paper are part of the Natural

MMSP'10, October 4-6, 2010, Saint-Malo, France.
???-?-????-????-?/10/$??.??

Interactive Walking (NIW) FET-Open project[1], whose goal is to provide closed-loop interaction paradigms enabling the transfer of skills that have been previously learned in everyday tasks associated to walking. In the NIW project, several walking scenarios are simulated in a multimodal context, where especially audition and haptic feedback play an important role.

II. Simulation Software

We developed a physically based synthesis engine able to simulate the auditory and haptic sensation of walking on different surfaces. Acoustic and vibrational signatures of locomotion are the result of more elementary physical interactions, including impacts, friction, or fracture events, between objects with certain material properties (hardness, density, etc.) and shapes. The decomposition of complex everyday sound phenomena in terms of more elementary ones has been an organizing idea in auditory display research during recent decades [10]. In our simulations, we draw a primary distinction between solid and aggregate ground surfaces, the latter being assumed to possess a granular structure, such as that of gravel.

Fig. 2. A picture of one pressure sensor and two actuators embedded in the shoes.

This model and its discretization are described elsewhere in detail [3]. The model has been recently adapted to the audio simulation of footsteps [15]. Here, we used the same model to drive the haptic and the audio synthesis. It is briefly recalled below.

A footstep sound may be considered to cause multiple micro-impacts between a sole, i.e., an *exciter*, and a floor, i.e., a *resonator*. Such interaction can be either discrete, as in the case of walking on a solid surface, or continuous, as in the case of a foot sliding across the floor.

In the simulation of discrete impacts, the excitation is brief and has an unbiased frequency response. The interaction is modelled by a Hunt-Crossley-type interaction where the force, f, between two bodies, combines hardening elasticity and a dissipation term [12]. Let x represent contact interpenetration and $\alpha > 1$ be a coefficient used to shape the nonlinear hardening, the special model form we used is

$$f(x, \dot{x}) = -kx^{\alpha} - \lambda x^{\alpha}\dot{x} \quad \text{if } x > 0, \quad 0 \text{ otherwise.}$$

The model described was discretized as proposed in [2].

If the interaction called for slip, we adopted a model where the relationship between relative velocity v of the bodies in contact and friction force f is governed by a differential equation rather than a static map [7]. Considering that friction results from a large number of microscopic damped elastic bonds with an average deflection z, a viscous term, $\sigma_2 v$, and a noise term, $\sigma_3 w$, to represent roughness, we have

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

The force specified by these models is applied to a virtual mass which produces a displacement signal that is then processed by a linear shaping filter intended to represent the resonator. A solid surface is represented by an impact and a slide. The impact model alone was used to recreate the sound and the feel produced when walking on wood. The friction model was tuned to simulate walking on creaking wood.

To simulate walking on aggregate grounds, we used a physically informed sonic models (PhiSM) algorithm [4]. Stochastic parameterization is employed to simulate particle interactions thereby avoiding to model each of many particles explicitely. Instead, the particles are assigned a probability to create an acoustic waveform. In the case of many particles, the interaction can be represented using a simple Poisson distribution, where the sound probability is constant at each time step, giving rise to an exponential probability weighting time between events.

III. Simulation Hardware

In order to provide both audio and haptic feedback, haptic shoes enhanced with pressure sensors have been developed. A pair of light-weight sandals was procured (Model Arpenaz-50, Decathlon, Villeneuve d'Ascq, France). This particular model has light, stiff foam soles that are easy to gouge and fashion. Four cavities were made in the tickness of the sole to accommodate four vibrotactile actuators (Haptuator, Tactile Labs Inc., Deux-Montagnes, Qc, Canada). These electromagnetic recoil-type actuators have an operational, linear bandwidth of 50–500 Hz and can provide up to 3 G of acceleration when connected to light loads. As indicated in Figure 1 and Figure 2, two actuators were placed under the heel of the wearer and the other two under the ball of the foot. There were bonded in place to ensure good transmission of the vibrations inside the soles. When activated, vibrations propagated far in the light, stiff foam. In the present configuration, the four actuators were driven by the same signal but could be activated separately to emphasize, for instance, the front or back activation, to strick a balance, or to realize other effects such

[1]http://www.niwproject.eu/

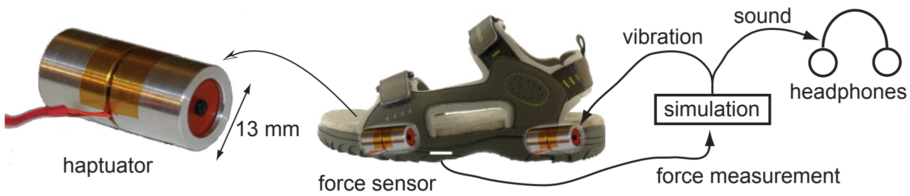

Fig. 1. System (one shoe shown). Left: recoil-type actuation from Tactile Labs Inc. The moving parts are protected by an alumimum enclosure able to bear the weight of a person. Middle: approximate location of the actuators in the sandal. Right: system diagram showing the interconnections.

as modulating different, back-front signals during heel-toe movements.

The sole has two force sensitive resistors (FSRs) pressure sensors[2] whose aim is to detect the pressure force of the feet during the locomotion of a subject wearing the shoes. The two sensors are placed in correspondence to the heel and toe respectively in each shoe.

The analogue values of each of these sensors are digitized by means of an Arduino Diecimila board[3] and used to drive the audio and haptic synthesis.

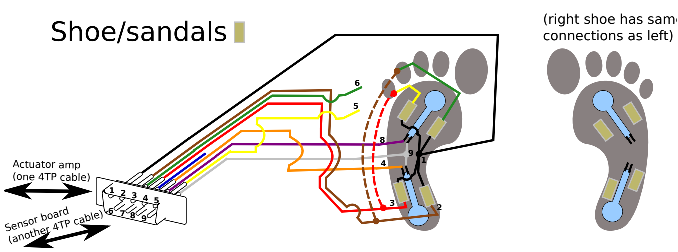

Fig. 3. Schematic representation of the cabling required to run sensors and actuators for one shoe.

A cable exits from each shoe, with the function of transporting the signals for the pressure sensors and for the actuators. Such cables are about 5 meters long, and they are connected through DB9 connectors to two 4TP (twisted pair) cables. One 4TP cable carries the sensor signals to a breakout board which contains trimmers, that form voltage dividers with the FSRs, which then interfaces to an Arduino board. The other 4TP cable carries the actuator signals from a pair of Pyle Pro PCA1[4] mini 2X15 W stereo amplifiers, driven by outputs from a FireFace 800 soundcard.[5] Each stereo amplifier handles 4 actuators found on a single shoe, each output channel of the amplifier driving two actuators connected in parallel. The PC handles the Arduino through a USB connection, and the FireFace soundcard through a FireWire connection. The connection among the different elements of the system is illustrated in Figure 4.

IV. Implementation

Using the algorithms just described we implemented a comprehensive collection of footstep sounds.

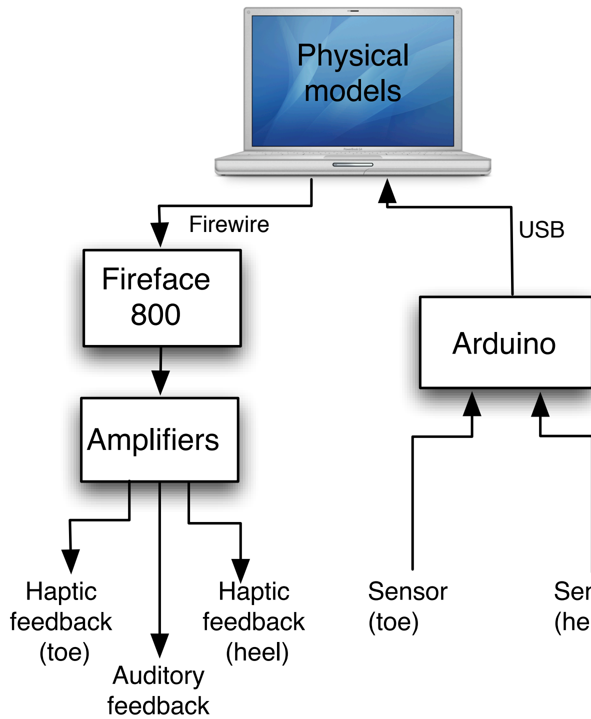

Fig. 4. Diagram illustrating the different hardware components of the system, together with their connections to the PC. The representation is for one shoe.

The sound synthesis algorithms were implemented in C++ as external libraries for the Max/MSP sound synthesis and multimedia real-time platform.[6] To enable compatibility with the Pure Data platform, [7] the algorithms were implemented using Flext.[8] One of the challenges in implementing the sounds of different surfaces was to find the suitable combinations of parameters and their range of variations which provided a realistic simulation. In our simulations, designers have access to a sonic palette making it possible to manipulate all such parameters, including material properties.

[2] I.E.E. SS-U-N-S-00039
[3] http://arduino.cc/
[4] http://www.pyleaudio.com/manuals/PCA1.pdf
[5] http://www.rme-audio.com/english/firewire/ff800.htm
[6] www.cycling74.com
[7] www.puredata.org
[8] http://puredata.info/Members/thomas/flext

The synthesized sounds have also been enhanced with reverberation algorithms. For this purpose we experimented with two approaches. The first was an algorithmically generated reverb working in real time, implemented as external for Max/MSP, called gigaverb∼. [9] The second made use of the technique of convolving a signal with a impulse response; such an approach was possible in real time, thanks to an external object allowing convolution with zero latency. [10]

The best results in sound quality were found using the second approach, which allowed to render more realistically the sizes of various kinds of indoor environments according to the impulse response chosen.

V. Controlling the engine

The footsteps synthesizer has been designed and implemented to be controlled by a unique input parameter, that is the ground reaction force (GRF). The real-time extrapolation of a GRF from the signals coming from the sensors turned out to be not the right choice for the control of the sound synthesis engine because of the features of the signal itself. For that reason we opted for a solution based on recorded GRF files and on a system of thresholds applied both on the signals and on their first derivatives. In particular, we used the values of the first derivative as control for triggering, into the footsteps synthesizer, some GRFs corresponding to heel or toe according to the activated sensor.

While a subject walks there is a variation of the values of the pressure sensors in correspondence to each step. Such variation is the basis for obtaining first time derivatives of the sensors signals, which remain related to the intensity with which the foot hits the ground. Each time the value of the first derivative becomes bigger than a threshold, the GRF corresponding to the activated sensor is triggered into the engine. More precisely we checked only positive changes in the derivative value, since we were interested in the generation of the sound when the step hits – and not when it leaves – the ground. Other thresholds, both on the signals and on their first derivatives, were used in order to handle some boundary conditions, like the standing of the subject, with the aim of controlling the generation of sound. Such thresholds are set in a phase of calibration of the system, which has to take into account the different weights of the subjects wearing the shoes, in order to have an average value suitable for all the possible cases.

The GRFs triggered have been created by extracting the amplitude envelope from audio files of recorded footsteps on concrete, divided into heel and toe components. Such sounds were chosen among those available on the Hollywood Edge sound effects library. [11] Five types of heel and toes audio files were used and randomly chosen at the moment of the triggering, giving rise to 25 possible combinations. Such behavior has been adopted in order to not have always the same GRF as input of the engine, and this allows to have differences in the generated sounds at every step, increasing thus the degree of realism of the walking experience.

The input GRF controls directly all or some of the parameters of the various algorithms, as well as the range of variation of the amplitudes of both the subcomponents and global sound. Figure 5 shows the waveform of one of the footstep sounds used and its corresponding extracted GRF. The GRF was calculated from the input signal extracting its amplitude envelope. To perform envelope extraction we used a simple non-linear low-pass filter proposed by Cook in [16]:

$$e(n) = (1 - b(n))|x(n)| + b(n)e(n-1)$$

where

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

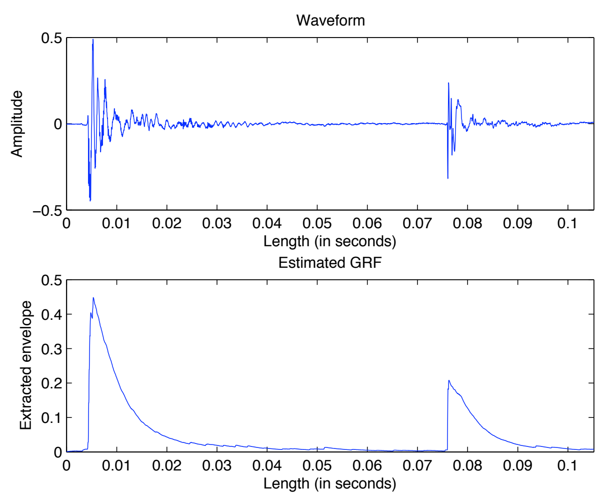

Fig. 5. *Time domain waveform of the used footstep on wood (top) and its relative extracted GRF (bottom).*

Figure 6 shows on top a waveform of a characteristic signal captured by a pressure sensor, and its derivative on the bottom. It is possible to notice the spikes on the derivative, which were used as time information for triggering a corresponding GRF.

VI. Evaluation of the system

The system has been evaluated by using it both offline and interactively. The complete results of this evaluation are described in [14], [17]. Here, we limit ourselves to summarize the interesting results, which can help in the development of the next shoe prototype. Overall, results show that subjects are able to recognize most of the synthesized surfaces with high accuracy. Results moreover confirm that auditory modality is dominant on the haptic

[9]Available at http://www.akustische-kunst.org
[10]http://www-users.york.ac.uk/ ajh508/index.html
[11]www.hollywoodedge.com/.

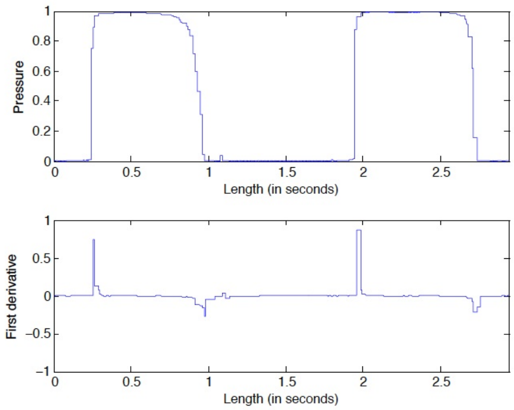

Fig. 6. Waveform of a characteristic signal captured by the pressure sensors (top), and its derivative (bottom).

modality and that the haptic task was more difficult than the other two. This can be due to the low sensitivity of the foot when exposed to haptic signals. Such results can also be improved by the design of more powerful actuators, which are currently under development. It is interesting to notice that similar accuracy can be observed in the recognition of real recorded footsteps sounds, which is an indication of the success of the proposed algorithms and their control.

VII. Conclusion

In this paper, we introduced a real-time footsteps synthesizer able to provide audio and haptic feedback, and which is controlled by the user during the act of walking by means of shoes embedded with sensors and actuators.

The developed system is ready to be integrated in computer games and interactive installations where a user can navigate. In future work, we indeed plan to utilize the system in multimodal environments including visual feedback, to understand the role of the different sensorial modalities to enhance sense of immersion and presence in scenarios where the act of walking plays an important role.

Acknowledgment

The research leading to these results has received funding from the European Community's Seventh Framework Programme under FET-Open grant agreement 222107 NIW - Natural Interactive Walking. [12]

References

[1] F. Avanzini and P. Crosato. Haptic-auditory rendering and perception of contact stiffness. *Lecture Notes in Computer Science*, 4129:24, 2006.

[2] F. Avanzini and D. Rocchesso. Modeling collision sounds: Non-linear contact force. In *Proc. COST-G6 Conf. Digital Audio Effects (DAFx-01)*, pages 61–66, 2001.

[3] F. Avanzini, S. Serafin, and D. Rocchesso. Interactive simulation of rigid body interaction with friction-induced sound generation. *IEEE transactions on speech and audio processing*, 13(5 Part 2):1073–1081, 2005.

[4] P. Cook. Physically Informed Sonic Modeling (PhISM): Synthesis of Percussive Sounds. *Computer Music Journal*, 21(3):38–49, 1997.

[5] P. Cook. Modeling Bill's Gait: Analysis and Parametric Synthesis of Walking Sounds. *Proceedings of the AES 22nd International Conference on Virtual, Synthetic, and Entertainment Audio*, pages 73–78, 2002.

[6] D. DiFranco, G. L. Beauregard, and M. Srinivasan. The effect of auditory cues on the haptic perception of stiffness in virtual environments. *Proceedings of the ASME Dynamic Systems and Control Division.*, 1997.

[7] P. Dupont, V. Hayward, B. Armstrong, and F. Altpeter. Single state elastoplastic friction models. *IEEE Transactions on Automatic Control*, 47(5):787–792, 2002.

[8] A. Farnell. Marching onwards: procedural synthetic footsteps for video games and animation. *Proceedings of the Pure Data Convention*, 2007.

[9] F. Fontana and R. Bresin. Physics-based sound synthesis and control: crushing, walking and running by crumpling sounds. *Proc. Colloquium on Musical Informatics*, pages 109–114, 2003.

[10] W. Gaver. What in the world do we hear?: An ecological approach to auditory event perception. *Ecological Psychology*, 5(1):1–29, 1993.

[11] B. L. Giordano, S. Mcadams, Y. Visell, J. Cooperstock, H. Y. Yao, and V. Hayward. Non-visual identification of walking grounds. *Journal of the Acoustical Society of America*, 123(5):3412–3412, 2008.

[12] K. H. Hunt and F. R. E. Crossley. Coefficient of restitution interpreted as damping in vibroimpact. *ASME Journal of Applied Mechanics*, 42(2):440–445, 1975.

[13] S. Lederman. Auditory texture perception. *Perception*, 1979.

[14] R. Nordahl, A. Berrezag, S. Dimitrov, L. Turchet, V. Hayward, and S. Serafin. Preliminary experiment combining virtual reality haptic shoes and audio synthesis. In *Proc. Eurohaptics*, 2010.

[15] R. Nordahl, S. Serafin, and L. Turchet. Sound synthesis and evaluation of interactive footsteps for virtual reality applications. In *Proc. IEEE VR 2010*, 2010.

[16] L. Peltola, C. Erkut, P. Cook, and V. Valimaki. Synthesis of hand clapping sounds. *IEEE Transactions on Audio, Speech, and Language Processing*, 15(3):1021–1029, 2007.

[17] S. Serafin, L. Turchet, R. Nordahl, , S. Dimitrov, A. Berrezag, and V. Hayward. Identification of virtual grounds using virtual reality haptic shoes and sound synthesis. In *Proc. Eurohaptics symposium on Haptics and Audio-visual environments*, 2010.

[12] www.niwproject.eu