Audio-tactile Display of Ground Properties Using Interactive Shoes

Stefano Papetti[1], Federico Fontana[2], Marco Civolani[1],
Amir Berrezag[3], and Vincent Hayward[3]

[1] Università di Verona, Department of Computer Science
strada Le Grazie, 15 – 37134 Verona, Italy
{stefano.papetti,marco.civolani}@univr.it
[2] Università di Udine, Department of Mathematics and Computer Science
via delle Scienze, 206 – 33100 Udine, Italy
federico.fontana@uniud.it
[3] UPMC Universitè de Paris 06, Institut des Systèmes Intelligents et de Robotique
4 place Jussieu – 75005, Paris, France
amir.berrezag@isir.upmc.fr,hayward@cim.mcgill.ca

Abstract. We describe an audio-tactile stimulation system that can be worn and that is capable of providing the sensation of walking over grounds of different type. The system includes miniature loudspeakers and broadband vibrotactile transducers embedded in the soles. The system is particularly effective at suggesting grounds that have granular or crumpling properties. By offering a broad spectrum of floor augmentations with moderate technological requirements, the proposed prototype represents a solution that can be easily replicated in the research laboratory. This paper documents the design and features of the diverse components that characterize the prototype in detail, as well as its current limits.

Keywords: Interactive shoes, foot-based interfaces.

1 Introduction

As a recent complement to the design and engineering of machine interfaces for the study of human locomotion, balance and equilibrium in walking [1], researchers in human-computer interaction have begun to address questions concerning the interactive display to humans of psychophysical cues at ground level. Initially concentrating on the visual modality, with a focus on interaction scenarios ranging mainly between performing arts and gaming, researchers have then recognized the importance of non-visual ground cues as means to enrich the interaction with floors through the feet [2]. As a result, some radically novel paradigms have emerged enabling users to experience multimodal floor augmentations that – in addition to the mentioned application fields – are expected to play roles also in rehabilitation, critical labor environment simulations and for navigation aids for both normally gifted and impaired people.

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Among such paradigms, those which are grounded on an *ecological* approach to interaction design appear to be especially promising [3]. For its strong potential to result into "natural" interactions that furthermore do not need any specific training or cultural probing, this approach has received specific attention especially by designers of non visual displays, in which implicit sonic and vibrotactile signals can be set to operate at the periphery of the focus of attention [4]. Notable results that can be ascribed to this approach include active floor installations using vibrotactile devices, capable of conveying realistic sensations of snow- and ice-covered grounds to users walking over them [5].

Floor-based setups offer virtually unlimited physical space where to locate sensors and actuators. Furthermore, the networking of different physical components just requires to connect them together via a wired communication infrastructure. Power connections are generally not a problem as well for non-mobile interfaces, such as active floors. Conversely, the realization of an infrastructure of this kind poses serious technical questions when the same interaction paradigm is exported to a mobile interface, that is, a pair of shoes.

In the mobile case basically all physical components need to be tailored in order to minimize size, weight and power consumption, meanwhile guaranteeing an acceptable performance of the interface. Moreover they must be robust, since they are moved around by users engaged in walking or running tasks. Under such working conditions, the measurement of the force exerted by the foot over a sole, the real-time computations which are needed to generate an output from time-varying force data, and the consequent display of realistic sound and vibrations from the shoes by means of active components become more difficult to be realized and kept stable across time.

In the following of this paper, the current development state of our project on interactive shoes is detailed so as to provide the reader with an in-depth vision on their design and engineering. Section 2 describes the concept. Section 3 forwards to a parallel publication in these proceedings, on the accurate measurement and analog-to-digital conversion of force data using cheap sensors and processing. Section 4 presents the software that is employed to generate feedback in real-time. Section 5 illustrates the characteristics and positioning of the haptic actuators and loudspeakers used for providing feedback. Finally, Section 6 briefly reports about the performances and current limits of the interface, furthermore outlining ongoing and future work.

2 Design Concept

During everyday walking tasks we are continuously exposed to changes in the floor properties. The perception of level and inclination allows walkers to maintain correct equilibrium and posture. In parallel, auditory and tactile ground cues provide significant detail about the floor characteristics [3]. By influencing gait and walking gestures, these cues determine our level of familiarity and confidence with ground surfaces. Blind persons make intensive use of such cues during their everyday way-finding and landmarking tasks across familiar environments.

Our interactive shoes aim at simulating changes in ground surface, by augmenting otherwise neutral (i.e., flat and homogeneous) floors. Augmented reality is receiving increasing recognition by interaction designers, for its potential to enrich our surrounding environments with additional information. As opposed to substitution, augmentation can smoothly alert of changing conditions and, if the warning messages are carefully designed, it can support user's decisions through the presentation of implicit (especially non-visual) signals [4]. Actuated shoes represent a significant instantiation of this concept, as they can display audio-tactile ground cues for purposes ranging from support to way-finding and landmarking, as mentioned before, up to rehabilitation, entertainment and simulations of immersive reality.

In a preliminary work, we have prototyped a pair of interactive shoes provided with force sensors and small loudspeakers, capable of generating auditory feedback in real-time by foot pressure data acquired during a walking task [6]. This prototype was able to concentrate all computational and power resources inside a backpack that could be worn by users. The interface, hence, could be made strictly mobile, and consequently it allowed total freedom of movement to users who could navigate, even for a long time, across an environment. We chose rubber clogs as they could be easily "hacked" by cutting, grooving, drilling their body. Thanks to these shoes we could test initial design ideas, especially concerning the choice and location of different types of sensors. On the other hand, the range of feet fitting with a single pair of clogs was limited to few sizes. This fact excluded a number of potential users from testing the prototype.

One important lesson that we learned from this preliminary prototype was that, as somehow expected already at the conceptual stage, substitution is far more difficult than augmentation. In other words, it is not easy to "cancel" the floor upon which one is walking meanwhile providing alternative ground surface properties. On the other hand, it is relatively easier to add simulated properties to the real floor by superimposing a layer of virtual material to it. So, for instance, turning a wooden floor into a marble surface would in principle require to mask the resonances coming from the wood, a goal that is clearly hard to achieve. As opposed to this, covering a "dry" material such as concrete with virtual gravel, dry leaves, or snow, is at reach of current feedback design techniques [2].

The recent introduction of vibrotactile actuators has resulted in a new prototype (see Fig. 1), that has dramatically improved the realism of the simulations. Furthermore, we have switched from clogs to sandals, as they can fit with a larger range of foot sizes. Thanks to a better positioning of the sensors – refer to Section 3 – we got satisfactory force detections by fastening feet sized between 38 and 44 (Italian standard scale) through the three buckles every sandal is provided with.

On the other hand, vibrotactile actuators are more demanding than small loudspeakers in terms of power consumption. For this reason a wired connection had to be planned in the current setup, to feed the actuators with high amplitude signals provided by a couple of power amplifiers. Holding this physical constraint, it was logical to locate all the physical components that do not need to reside

Fig. 1. Current shoe-based interface prototype

on the shoes (i.e., acquisition board, computer and output signal interface) off the wearable part of the interface.

A schematic of the components forming the prototype is illustrated in Fig. 2. Every shoe is provided with two force sensors, one small loudspeaker and two haptic actuators, all depicted within the rectangle in dashed line. The next sections detail such components, step by step.

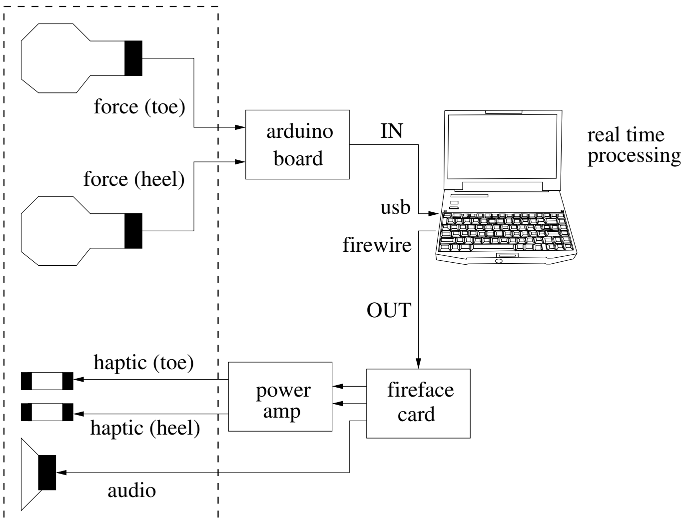


Fig. 2. Illustration of the prototype components. Sensors and actuators of one shoe are surrounded by the rectangle in dashed line.

3 Data Acquisition

The current implementation of the acquisition system presents a number of novelties that needed to expand this section into a self-contained paper, to which the reader is forwarded [7].

4 Real-Time Synthesis and Control

Interactive sounds are dynamic, informative, contextual, and occasionally bringing emotional content [8]. For this reason, sound design tools and systems should offer extensive control over the design process, generation, and interactive manipulation of sound.

Modern sound synthesis techniques, with their inherent parametric control, are able to handle continuous sound feedback in interactive contexts dynamically and effectively. In particular, physically-based synthesis models describe sonic interactions between resonating objects, and compute the resulting vibrations. Such vibrations are usually described in terms of signals accounting for local displacement and velocity of one or more objects. These signals can be directly sent to a loudspeaker. At the same time, they can drive a haptic device. Overall, physically-based models allow to maintain a tight coherence of the multimodal (in our case tactile and auditory) feedback.

For our specific purposes we made use of an open source software product called Sound Design Toolkit (SDT)[1] which is made of a set of physically-founded tools for designing, synthesizing and manipulating ecological sounds in real time. SDT consists of a library of external objects (*externals*) and programs (*patches*) for the real-time DSP environments Max/MSP and Pure Data (Pd). In particular, each external represents a physically-based or -inspired algorithm for sound synthesis or control, while the SDT patches combine those externals into complete control and sound models.

Below, first a brief description of the models providing audio-haptic feedback is given. Afterwards, an explanation is provided on how such models are controlled by making use of the data coming from the force sensors.

4.1 Physical Models of Contact Events

Contacts between solid bodies form a large class of sonic phenomena in everyday environments, and it has been shown that many contact interactions can be successfully simulated by using a flexible one-dimensional impact or friction model. Regarding this, short acoustic events like impacts can strongly gain or change in expressive content when set, for example, in an appropriate temporal sequence [9].

[1] The SDT is freely available from the following SVN repository: `https://svn.sme-ccppd.org/svn/sobs/SoundDesignTools/`

Soft Impact. The SDT *soft impact* model allows to synthesize the sound of impact on a soft surface, or of soft impact between two surfaces. The soft impact algorithm [10] exploits a rather simplified yet effective approach. Indeed the algorithm is physically-inspired, but it mainly focuses on the actual acoustic result: no actual interaction between objects is simulated, instead the algorithm exploits a filtered noise burst – representing a force signal – to excite a modal resonator [11]. The rationale behind the algorithm can be qualitatively justified considering that non-sharp contacts can be reduced to dense sequences of micro-impacts, thus in a sense discretizing the surfaces of the interacting objects as multiple contact areas. Also, the use of specifically filtered noise signals can be motivated considering that such micro-impacts can have a quasi-random character.

The available model parameters allow for full control of the modal resonator, an ADSR envelope (*attack time*, *decay time*, *sustain gain*, *sustain time*, *release time*), and the *cut frequencies* of two filters (respectively, high- and low-pass) which process the noise burst.

The *soft impact* model has been used to simulate the contact between a shoe and homogeneous floors or wet grounds, in particular providing two separate envelopes corresponding respectively to the heel and the toe. The aim was to add resonances to neutral floors in order to change the perceived ground material: for instance, a floor made of concrete can be augmented so as to resonate and vibrate like a wooden floor, or as a marshy ground.

Crumpling. The SDT *continuous crumpling* model [12,13] is the result of an *ad hoc* control layer superimposed to a low-level impact model. Similarly to the soft impact model, the crumpling algorithm does not actually model physical contacts between solid objects but, rather, time sequences of crumpling events, represented by groups of impact events. These sequences provide data that drive the evolution across time of the impact model parameters.

Both the temporal distribution of crumpling events and their own power follow stochastic laws which are derived from physics [14]. Such laws govern 1) the energy dissipation occurring during an impact, and 2) the temporal distribution of adjacent events. Each phenomenon exposes a characteristic parameter, resulting in the control of the average interval between events and the average power of impacts, respectively.

As for the actual implementation of the algorithm, the user is provided with several physically meaningful parameters, which allow to set: the applied *force* giving rise to crumpling events and being proportional to their average power, and the *resistance* put up by the material being crumpled, corresponding to the granularity of the latter.

In the perspective of simulating virtual aggregate grounds, the resistance parameter allows control of the compactness of the ground (the lower the resistance, the smoother and more uniform the sequence of crackling events), while the force parameter – being proportional to the energy of the micro-impact events – can be mapped directly to the pressure exerted by the foot on the ground.

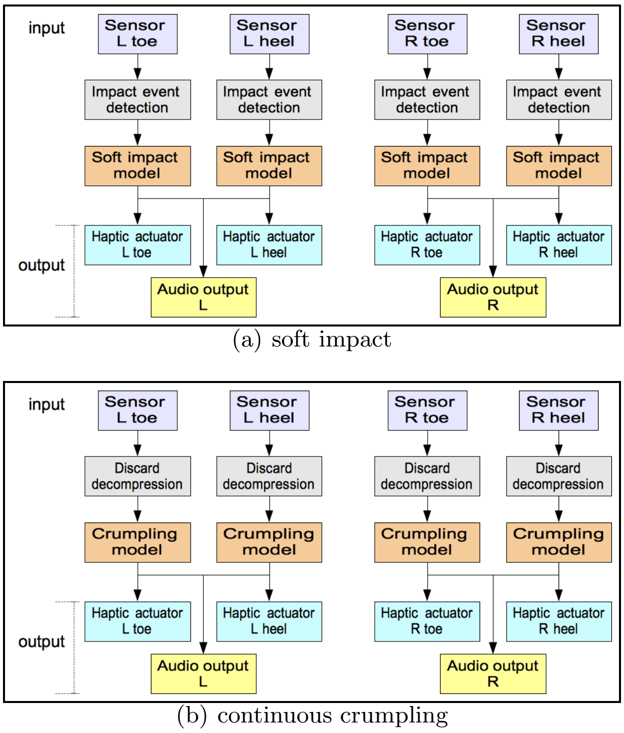


Fig. 3. Diagram explaining the use of the *soft impact* and *continuous crumpling* models. The diagrams display connections, data conditioning and signal outputs driving both the audio and the haptic feedback.

These models have already been successfully exploited for synthesizing sounds and haptic feedback in simulations of walking on aggregate grounds [15], furthermore they have been adapted for simulating the sound of walking on icy snow, creaking floors, brushwood.

4.2 Data Conditioning and Synthesis Control

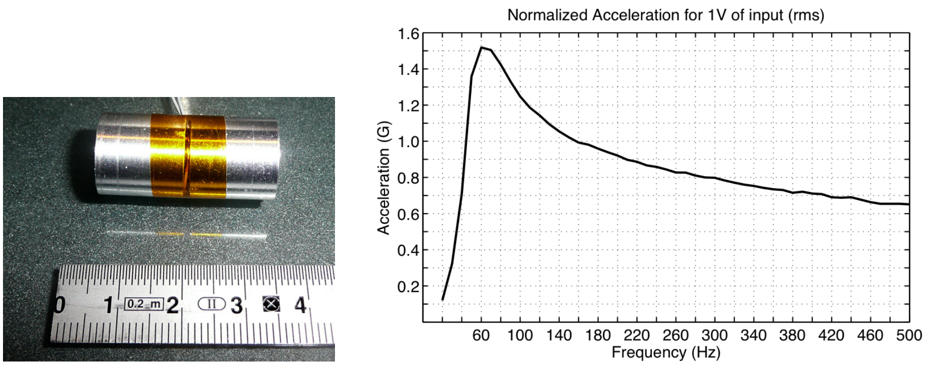
The high-rate data stream coming from the Arduino accounts for the force signals measured at each foot's toe and heel. These four signals are received by a Pd patch communicating with the Arduino, and then routed to the SDT model in use. Moreover, the same patch can save the force signals as text files (especially useful for e.g. offline analysis), and later reproduce such files in a way to control the SDT models with prerecorded data.

As for the *soft impact* model, the force signals coming from the sensors are used to trigger four individual noise bursts which excite a resonating object modeling the ground. More in detail, a simple algorithm is used which detects impact events occurring at both the heel and the toe. As soon as such an event is detected, the current force value is used to set the amplitude of the corresponding noise burst: the larger this amplitude, the more energetic the micro-impacts on the resonating object. See the diagram in Fig. 3(a) for an explanation of the use of the *soft impact* model.

Thanks to its external interface, the *continuous crumpling* continuously maps gestures into force parameters: in fact, the model reacts only to variations in the applied force, this way filtering out constant components that do not reflect active interactions. In this regard, the force signals coming from the four sensors have been mapped to the force parameters of four separate instances of the *crumpling* model. By considering that aggregate grounds dynamically respond to a foot falling on them or scraping over them, it was hypothesized that the model should provide energy proportionally to the changes in the force, accounting for corresponding variations of the foot compression. To this end, a gate function has been employed which filters out negative variations of the force, thus excluding feedback when the foot depresses the ground. See the diagram in Fig. 3(b) for an explanation of the use of the *continuous crumpling* model.

5 Vibrotactile and Audio Feedback

Vibrotactile feedback is produced by two vibrotactile transducers embedded in the front and the rear of the shoe sole respectively (Fig. 4(a)) [16] (Haptuator, Tactile Labs Inc., Deux-Montagnes, Qc, Canada). Two cavities were made in the soles to accommodate these broadband vibrotactile actuators. 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. They were bonded in place to ensure good transmission of the vibrations inside the soles. When activated, vibrations propagated well in the light, stiff foam. An improved type of such actuators is currently being deployed. This new type uses



(a) (b)

Fig. 4. Haptic actuator: (a) Architecture. (b) Characteristic response (from TactileLabs Inc.).

multiple magnets instead of just one, in a configuration designed to concentrate the magnetic flux on a small region. They also benefit from a new suspension design that expends the low-end response significantly and boost the vibratory power despite being of 10 mm in diameter. Such a small size makes it possible to embed them in a variety of objects. Due to their design and structure they can be immersed in the inside of a sole, meanwhile they are able to support the weight of a person with a very little vertical deflection, yet free to vibrate in the horizontal direction because of its anisotropic structure.

In addition to vibrations, each shoe emits sounds from one Goobay Soundball Mobile battery loudspeaker mounted on the top buckle (see Fig. 1). These devices are provided with on-board micro-amplifiers, hence they can be connected directly to the audio card. As any small, low-power loudspeaker device, they exhibit unavoidable performance limits both in the emitted sound pressure level (2.4 W RMS) and low frequency cutoff (about 200 Hz).

The former limit does not pose problems as far as an ecological loudness level of the walking sounds is set. Large levels can be obtained at the cost of audible distortion and faster discharge time of the battery.

The latter limit has perceptual implications instead, as walking interactions can give rise to acoustic energy also in the low frequency. This energy, however, is the result of resonances that are consequence of slowly decaying, large wavelength vibrations occurring in certain floors when they are excited by a shoe impacting over them—think of a floor made with a layer of large wooden bars or panels, for instance. In this sense, forcing a sonic shoe to reproduce low frequencies has no ecological meaning. Due to the aforementioned physical mechanism, it is in fact the floor that should display unlocalized low-frequency sounds on a large area while mimicking the dissipation of mechanical energy that has been transferred when someone walks over it.

5.1 Low and High Frequency Routing

For their efficiency in the high frequency band the small loudspeakers radiate acoustic waves that, by defining a shortest path to the listener's ears and for their strong directivity, create a neat localization of the sound source in correspondence of the shoes. By arriving at the ears later than such waves, any other auditory stimulus is aggregated to the same source location by the listeners due to the known *precedence* effect.

As opposed to small loudspeakers, the haptic actuators generate components in the low frequency. A look to Fig. 4(b) in fact shows that the response of the actuators lies approximately above 50% of the 60 Hz peak value in the range 50-300 Hz. Part of the mechanical energy that they emit, in the form of vibrations across this range, is transmitted to the floor through the shoe sole. Although not comparable with the vibrations of a floor surface that naturally resonates at those frequencies, this energy propagates across the ground and can be heard in the proximity of the walking area. In conclusion, the haptic actuators mitigate the absence in the interface of mid-range loudspeakers and woofers, capable of adding sound energy in the low frequency band.

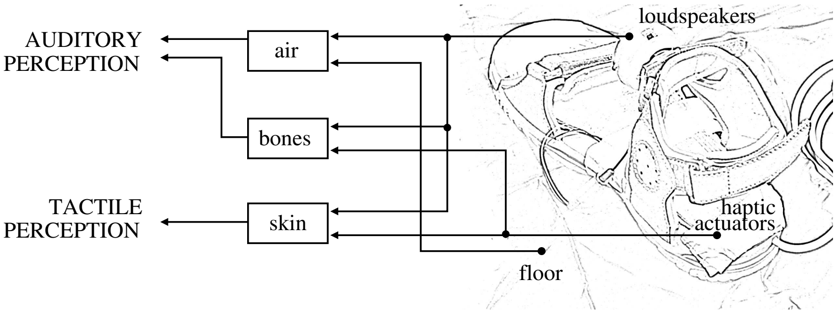


Fig. 5. Information paths connecting the actuated shoes to the auditory and tactile perception

In addition to this effect, a fraction of the vibrational energy that reaches the foot is probably transmitted to the auditory nerve through bone conduction. The set of potentially active information paths connecting the actuated shoes to our perceptual system are illustrated in Fig. 5.

To gain control of this information we have included some filters, all at software level, before routing the digital signal to the various channels in Fig. 2. Specifically, they include high-pass filters that cut off components below 20 Hz otherwise incoming to the output devices, and a smooth resonator that equalizes the response in Fig. 4(b) in the range 50-200 Hz, meanwhile cutting off the frequency components that lie outside the active range of the haptic actuator.

By significantly reducing the energy of the signal that is off the admissible band of the respective devices, these stages contribute to minimize the distortion artifacts and spurious frequency components otherwise introducing unpredictable effects in both the haptic actuators and small loudspeakers.

A systematic inspection of the contribution to listening and touch of the diverse sources of audio and vibrotactile signal, illustrated in Fig. 5, is far from being straightforward. If, on the one hand, their individual effects have been clearly experienced by anybody who informally tested the prototype, on the other hand a quantitative analysis of the perceptual impact of the vibrational energy propagating through the skin, in connection with the acoustic energy propagating through the air and conducted by the bones, would be worth opening another research chapter. In fact, not only the auditory and tactile percepts are difficult to be isolated in presence of a spatially concentrated audio and haptic stimulation, but also the coherence of the resulting (acousto-tactile) multimodal percept is probably conditioned by—perhaps even illusory—cross-modal effects occurring between the two modalities [17]. All this complexity at least does not affect the localization of sounds, for the precedence effect mentioned at the beginning of this section.

6 Conclusions and Future Work

One of the most important achievements of the proposed interface resides in the low latency of the feedback. Due to the excellent features of the audio card and its drivers, the efficiency of the real-time synthesis is not destroyed by bottlenecks encountered at the I/O stages of the system. More in general, this performance has come out as a result of trying many configurations among various operating and hardware systems, and by repeatedly refining the firmware of the acquisition board and the patches in Pd. Measurements made using an oscilloscope connected to the loudspeaker output, and triggered by an input from the audio card simulating a change in force signal, showed that this latency amounts to about 16 ms using the crumpling model.

The analysis of force data is not yet ready to resolve elaborate foot gestures and locomotion tasks that differ from simple walking. Improvements can be made on this analysis, but a general solution to the accurate detection of force during foot movement is not behind the corner if cheap sensors are employed. For instance, sensors like those we used in our prototype saturate at few hundred Newtons, corresponding to some tens of kilos. Hence, they cannot measure changes in the force occurring when users keep standing on the toes or the heel while moving their feet.

The cable connecting the shoes to the amplifiers represents a technological limit of the prototype, that will not be solved unless a new generation of power-efficient haptic devices becomes available.

In spite of these limits, the performance of the prototype is by all means encouraging. Ongoing research deals with the measurement of the skin displacement elicited by the haptic actuators, and with perceptual experimentation on a specific cross-modal effect induced by the multimodal feedback.

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