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Natural Interactive Walking

Deliverable 4.2

MULTIMODAL DISPLAY OF VIRTUAL ATTRIBUTES AND FLOOR EVENTS IN WALKING INTERFACES

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Contents

1 Introduction

This document reports on the activities performed by the partners of the NIW consortium from October 2009 to September 2010. Such activities are related to the simulation of multimodal feedback.

We first describe the development of shoes with audio and haptic feedback performed both at AAU and UNIVR. Such developments were made possible thanks to the actuators provided by UPMC. We then describe an audio-visual simulation of bumps and holes, which is the result of a collaboration between AAU and INRIA. We then report on activities related to the multimodal rendering of 2D fracture performed at McGill University. We the describe an audio-visual simulation of fluids and a novel interaction paradigm called ”magic barrier tape” performed at INRIA. we furthermore report on the work performed at INRIA related to a novel approach to haptic interaction with simulated fluids. Finally we The technology presented in this deliverable has been extensively evaluated, and the results of the evaluation are described in Workpackage 5.1. Related publications can be found in the private area of `www.niwproject.eu`.

2 Audio-haptic simulation based on active shoes (AAU and UNIVR)

Both AAU and UNIVR have immediately taken advantage of the UPMC miniaturized haptic devices, by embedding them in the (previously audio-only) active shoe prototype that has been re-designed for the occasion. In both locations, the new prototype was ready to work at project month 14, immediately after the actuators from UPMC were provided.

Later on that date, a dense software and firmware engineering as well as experimental evaluation activity has been launched around the prototype. The components of this activity are documented respectively in the deliverables 3.2 and 5.1, both published in parallel to this document.

Conversely, in this deliverable the active shoe design is addressed. Specifically, we report a summary of [15], reposited in the private area of `www.niwproject.eu`, in which a detailed description of the prototype can be found.

2.1 Introduction

As known by the previous deliverables, our interactive shoes aim at simulating changes in ground surface by augmenting otherwise neutral (i.e., flat and homogeneous) floors. The active shoes design concept is grounded on an *ecological* approach to interaction design. This approach in fact appears to be especially promising [8], due to its strong potential to result into "natural" interactions that furthermore do not need any specific training or cultural probing. For this reason, it 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 [13].

Contrarily to floor-based setups, which offer virtually unlimited physical space where sensors and actuators can be networked together via a wired communication infrastructure and furthermore powered directly, the realization of a foot-based interface poses serious technical questions when a walking interaction paradigm is implemented. In practice, 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.

Due to the aforementioned constraints, and especially because of the notable power needed by the haptic actuators, the current shoe prototype has required to be wired to a located (i.e., non wearable) setup including a power amplifier. This requirement has limited the mobility of users to about 10 m, as opposed to what they could do using the previous, auditory only prototype whose computing and power components could be put in a backpack hence allowing for virtually unlimited navigation.

In spite of this limitation, a subjective mobility of few meters has permitted to perform all the needed tests and evaluation experiments that had been planned.

Figure 2.1: Current shoe-based interface prototype.

2.2 Current concept

One important lesson that we learned from the 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 [17].

The recent introduction of vibrotactile actuators has dramatically improved the realism of the simulations. The current prototype (see Fig. 2.1) is based on sandals. Compared to clogs, that we had previously adopted, sandals fit with a larger range of foot sizes. Also thanks to a better positioning of the sensors, 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. 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 2.6 and Figure 2.7, 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 as modulating different, back-front signals during heel-toe movements.

As already anticipated in the introduction, 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 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. 2.2. Every shoe is provided with two force sensors, one small loudspeaker and two haptic actuators, all depicted within the rectangle in dashed line.

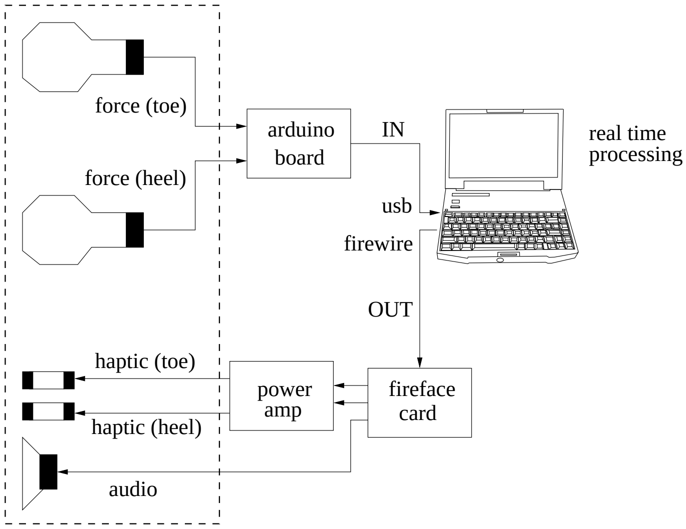


Figure 2.2: Illustration of the prototype components. Sensors and actuators of one shoe are surrounded by the rectangle in dashed line.

The acquisition components are detailed in Deliverable 3.2.

The sole has two force sensitive resistors (FSRs) pressure sensors[1] 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[2] and used to drive the audio and haptic synthesis.

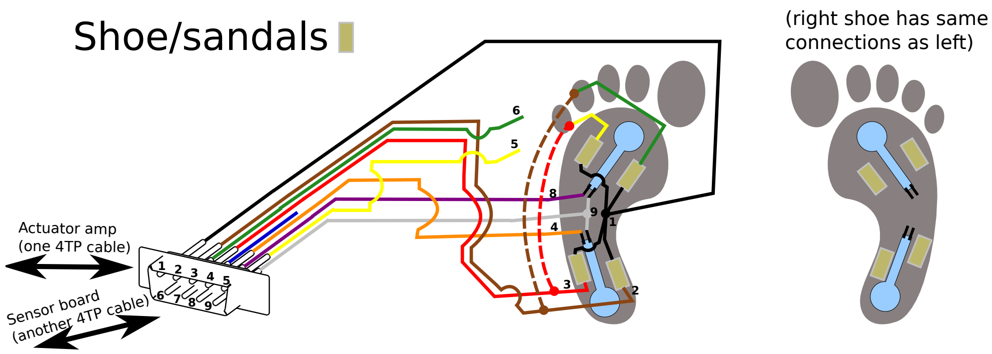
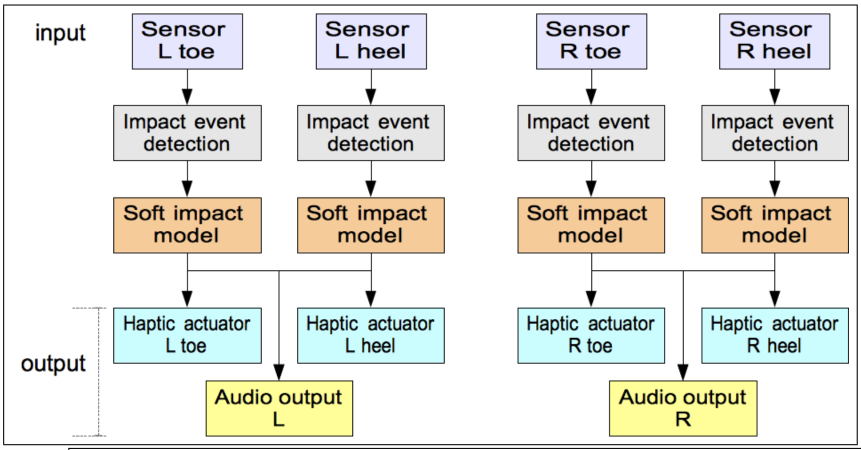


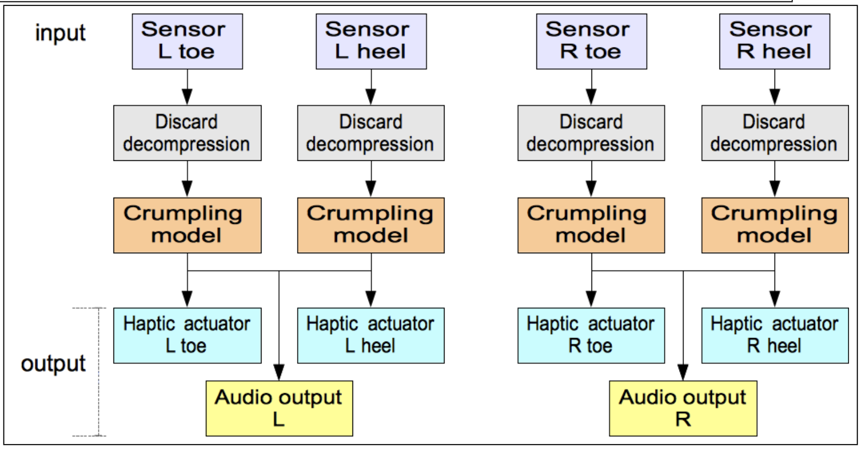
Figure 2.3: Schematic representation of the cabling required to run sensors and actuators for one shoe.

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[3] mini 2X15 W stereo amplifiers, driven by outputs from a FireFace 800 soundcard.[4] 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

[1] I.E.E. SS-U-N-S-00039
[2] http://arduino.cc/
[3] http://www.pyleaudio.com/manuals/PCA1.pdf
[4] http://www.rme-audio.com/english/firewire/ff800.htm



[soft impact]



[continuous crumpling]

Figure 2.4: 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.

soundcard through a FireWire connection. The connection among the different elements of the system is illustrated in Figure 2.5.

2.3 Simulation Software

Real-time synthetic feedback is based on the open source software product called Sound Design Toolkit (SDT), which is made of a set of physically-founded tools for designing, synthesizing and manipulating ecological sounds in real time, and whose features have been detailed in Deliverable 4.1.

It is interesting to notice that both the audio and vibro-tactile feedback is generated by the same synthesis models, due to their physically-based nature. For the specific shoe-based context, the *soft impact* and *crumpling* models have been privileged. Fig. 2.3 and 2.4 essentially illustrate the use of such models in the specific application.

A physically based synthesis engine able to simulate the auditory and haptic sensation of walking on different surfaces was developed, based on SDT. 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 [7]. 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.

This model and its discretization are described elsewhere in detail [3]. The model has been recently adapted to the audio simulation of footsteps [12]. Here, we used the same model to drive the haptic

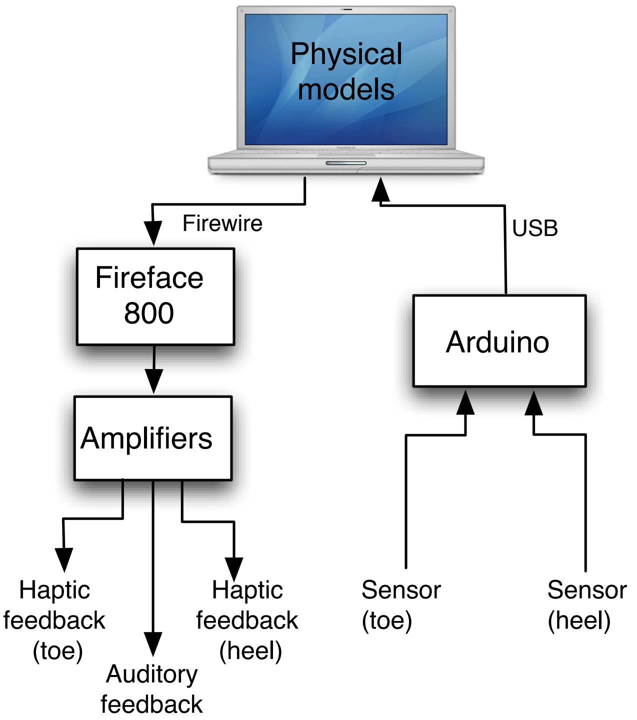


Figure 2.5: Diagram illustrating the different hardware components of the system, together with their connections to the PC. The representation is for one shoe.

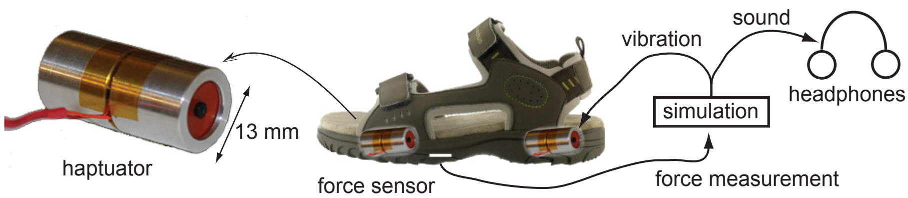


Figure 2.6: System (one shoe shown). Left: recoil-type actuation from Tactile Labs Inc. The moving parts are protected by an alumimum enclosure able to bear the weight of a person. Middle: approximate location of the actuators in the sandal. Right: system diagram showing the interconnections.

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 [10]. 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 [6]. Considering that friction results from a large number of microscopic damped elastic bonds

Figure 2.7: A picture of one pressure sensor and two actuators embedded in the shoes.

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 [5]. 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.

2.4 Implementation

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

The sound synthesis algorithms were implemented in C++ as external libraries for the Max/MSP sound synthesis and multimedia real-time platform.[5] To enable compatibility with the Pure Data platform, [6] the algorithms were implemented using Flext.[7] 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.

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~. [8] 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. [9]

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

[5] www.cycling74.com

[6] www.puredata.org

[7] http://puredata.info/Members/thomas/flext

[8] Available at http://www.akustische-kunst.org

[9] http://www-users.york.ac.uk/ ajh508/index.html

chosen.

2.5 Performances and open issues

Vibrotactile feedback is produced by two vibrotactile transducers embedded in the front and the rear of the shoe sole respectively. These transducers have been previously described in Deliverable 2.1 [9]. In addition to vibrations, each shoe emits sounds from one Goobay Soundball Mobile battery loudspeaker mounted on the top buckle (see Fig. 2.1).

The principal performance limit of the haptic feedback resides in the locality as well as directionality of the vibrations, both constrained by the position and orientation of the vibrotactile devices.

On the other hand, the small and low-power loudspeakers exhibit unavoidable performance limits both in the emitted sound pressure level (2.4 W RMS) and lower frequency cutoff (about 200 Hz). Low power does not pose problems as far as an ecological loudness level of the walking sounds is set. Conversely, the lack of low frequencies 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.

As opposed to their limits in the low frequency, small loudspeakers radiate acoustic waves in high frequency 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.

Conversely, the haptic actuators generate components in the low frequency. Part of the mechanical energy that they emit in 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 addition to propagation onto the floor, a fraction of the vibrational energy that reaches the foot is probably transmitted to the auditory nerve through bone conduction. 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.

The set of potentially active information paths connecting the actuated shoes to our perceptual system are illustrated in Fig. 2.8. However, the systematic inspection of the contribution to listening

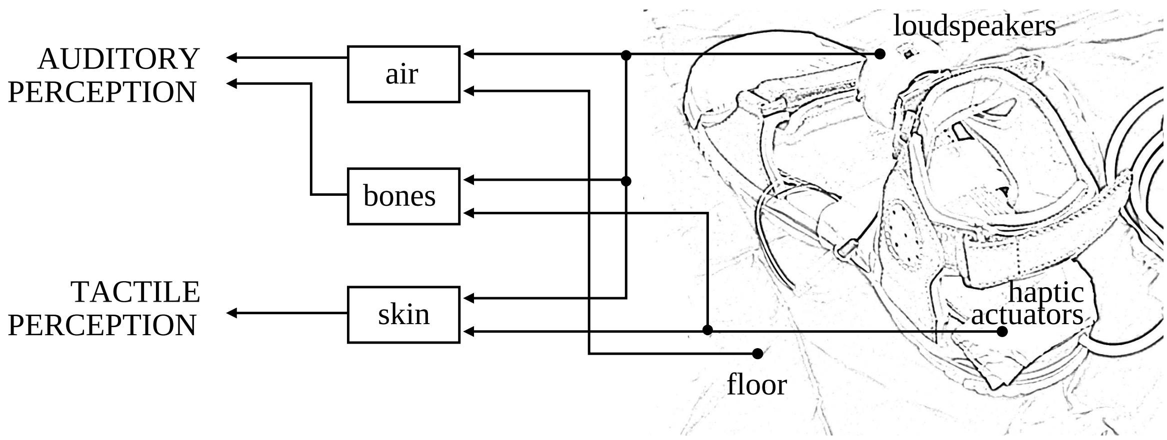


Figure 2.8: Information paths connecting the actuated shoes to the auditory and tactile perception.

and touch of the diverse sources of audio and vibrotactile signal 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 multimodal percept is conditioned by—even illusory—cross-modal effects occurring between the two modalities, as shown in Deliverable 5.1 and also noted by other researchers in audio-haptics [1]. All this complexity at least does not affect the localization of sounds, for the precedence effect mentioned at the beginning of this section.

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.

2.6 Conclusion on audio-haptic simulations

The actuators provided by UPMC significantly enhanced the quality and realism of the simulations, both at AAU and UNIVR. Both shoe prototypes were extensively tested, and the results of such tests are reported in Deliverable 5.1.

3 Audio-visual simulation of bumps and holes

(AAU and INRIA) In a collaboration between INRIA and AAU, the audio-visual sensation of walking on a bump or a hole was simulated. In this deliverable we present the way bumps and holes were simulated. Deliverable 5.1 reports on an experiment whose goal was to evaluate the ability of subject to recognize if they were walking on a bump or a hole, using auditory and visual cues.

3.1 The simulated environment

The virtual environment is a simple corridor with given dimensions (height=3.0m, length=12.6m, width=2.0m). There is a part in the center of the corridor where the height can be modified during the experiments: the user can walk either on a bump, a hole or a plane. To symbolize this variable part of the corridor, a transparent cube is represented on the ground with a height of 0.5m and a surface of 6.6mx2m, as illustrated in Figure 3.1. The variable height of the ground is not visible in order to exclude visual cues from the scene.

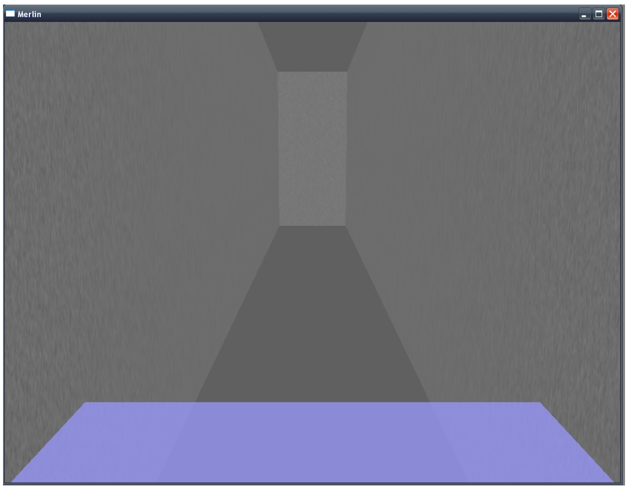


Figure 3.1: A screenshot at the beginning of a trial.

3.1.1 Visual feedback

The visual techniques used to simulate bumps and holes were the same proposed in [11]: a straightforward modification of the camera height (H), a modification of the camera navigation velocity (V), a modification of the camera orientation (O), and the combination of the three effects (HOV). Our simulations used a known mathematical profile, the gaussian one, which was used for the simulations of both holes and bumps.

Since the velocity techniques was used for the generation of the auditory feedback we briefly recall it here. The velocity effect is based on the variation of the camera velocity. Thus, the camera velocity is decreased when the user is going up and increased when the user is going down. We used a different algorithm for the ascending and descending cases. The algorithms compute the ratio R_{Velocity} applied between the real user velocity and the virtual camera velocity. The camera velocity is then modified following the equation:

$$\text{Velocity}^t = \text{Velocity}^{t-1} . R^t_{\text{Velocity}} \quad (3.1)$$

- Ascending case:

$$R^t_{\text{Velocity}} = exp(-R_{\text{AscendingV}} \,.\, \alpha^t) \tag{3.2}$$

where α is the tangent angle of the Gaussian curve and $R_{\text{AscendingV}}$ is a constant.
- Descending case:
This algorithm is designed to give a run up for a while after the bump or at the beginning of the hole. At time t, the ratio is updated regarding the difference between the user height in scene at times $t-1$ and t :

$$R^t_{\text{Velocity}} = R^{t-1}_{\text{Velocity}} + \Delta_{\text{Height}} \,.\, R_{\text{DescendingV}} \tag{3.3}$$

where the ratio $R_{\text{DescendingV}}$ is a constant. When the subject reaches the end of the descent, his speed is at a maximum. If he is walking in a hole, then he starts to go up and his speed value will be given by the ascending algorithm. If the subject is on a bump, he will reach the plane ground after the bump. His speed ratio R_{Velocity} will start decreasing at 0.1 unit per second, until another bump/hole is reached or the ratio is back to normal.

3.1.2 Auditory feedback

As concerns the sounds, the goal was to add to the images provided at the screen a consistent auditory feedback, but since we were interested just in a proof of concept no interaction between the visual and sound engines was created.
The technique adopted to render bumps and holes at auditory level has been the placement of footsteps sounds at different temporal intervals, taking as reference the work of the visual engine set with the velocity effect. In order to create a coherent mapping between the space travelled by the visual rendering along the surface and the temporal distances between steps, we chose to divide the surface profile in equal parts covering the same amount of space, and to place in those points a step (see Figure 3.2). Subsequently the temporal intervals to reach each point located on the curve have been calculated according to the equations utilized for the velocity effect by the visual engine (see section 3.1.1). Precisely, such calculations have been performed using the same parameters defining the gaussian curve (height and sigma), but modifying the values of the R factors regulating the lows for the ascending and descending case because of the necessity of synchronizing properly the two systems.

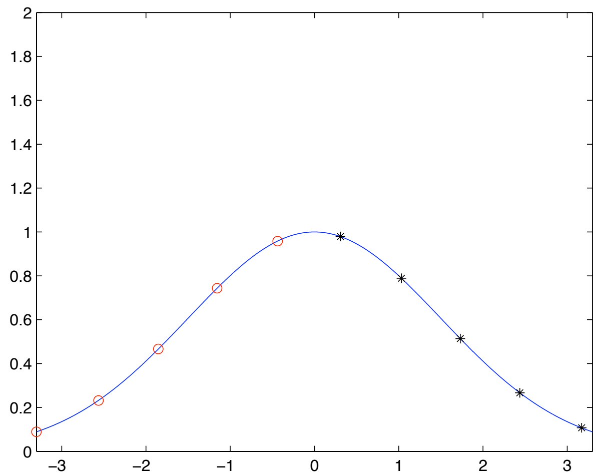


Figure 3.2: The gaussian profile used for a bump with the indication of the points in which the footstep sounds occur.

The input files for the sound synthesis engine resulting from such calculations, have been generated by means of MATLAB placing at different temporal patterns a single footstep sound (the same footstep was used to create the different stimuli presented to the subjects). The use of the same footstep was justified by the fact that we did not want other factors, such as changes in amplitude, to affect the results of the experiment. The footstep sound used was a recording of a real footstep on concrete.

The sound was chosen among those available in the Hollywood Edge sound effects library.[1]
For the purpose of this experiment, two types of surfaces, gravel and wood, were chosen. The reason for choosing two materials was to assess whether the surface type affected the quality of the results.

3.2 Evaluation of the bumps and holes simulation

As previously mentioned, the simulation of bumps and holes has been evaluated in an experiment which will be presented at the IEEE VRST conference and is reported in Deliverable 5.1.

[1] www.hollywoodedge.com/

4 Multimodal rendering of 2D fracture

(McGill)

In this research, we developed a simple algorithm for rendering plausibly realistic multimodal fracture in a two-dimensional surface underfoot [20]. It was implemented on the distributed multimodal floor array, and used contact-based sensing methods we developed for it, both of which are described in a prior publication [19], as reported in Deliverable 3.1.

The motivating scenario was based on a scenario involving a virtual frozen pond that users may walk on, producing patterns of surface cracks that are rendered via audio, visual, and vibrotactile channels. The algorithm synthesizes multimodal fracture events based on local foot-floor force information that is summarized by the localized contact pressure centroid $\mathbf{x}_c$ associated with the foot-floor pressure distribution produced by the footstep of a user (see [19]). The results are shown in Figure 4.1).

4.1 Audio and vibrotactile rendering

Audio and vibrotactile display channels provide feedback accompanying the fracture of the virtual ice sheet underfoot. The two are inspired by a local description of fracture at a crack front. Fracture events are described via an event time t_i and energy loss E_i. Figure 4.2 illustrates the continuum model and a simple mechanical analog used for synthesis. In the stuck state, the surface has stiffness $K = k_1 + k_2$ and is governed by:

$$F(t) = m\ddot{x} + b\dot{x} + K(x - x_0), \quad x_0 = k_2\xi(t)/K \tag{4.1}$$

where $\xi(t)$ represents the net plastic displacement up to time t. A Mohr-Coulomb yield criterion is applied to determine slip onset: When the force F_ξ on the plastic unit exceeds a threshold F_0 (either constant or stochastic), a slip event with incremental displacement $\Delta\xi(t)$, and energy loss ΔW, nominally representing the inelastic work of fracture growth, is generated. ΔW is sampled from an exponential distribution $p(E) \propto E^\gamma$ with material-related scale parameter γ [18]. Slip displacements are rendered as impulsive transients that excite a bank of modal oscillators with impulse response $s(t) = \sum_i a_i e^{-b_i t} \sin(2\pi f_i t)$, determined by amplitudes a_i, decay rates b_i, and frequencies f_i. An independent response is rendered in parallel for each tile.

4.2 Force-dependent crack animation

Although considerable research exists on the rendering of fracture in computer graphics, where surface cracks are often animated by simulating the inelastic evolution of a distributed stress state [16, 14], here, we adopt a computationally simpler and more efficient simulation method fusing the

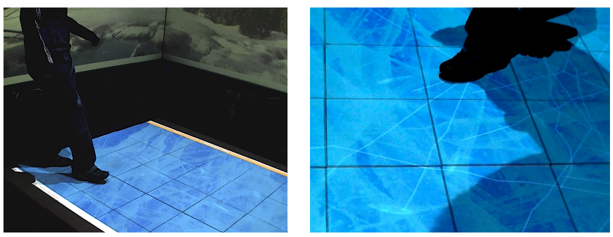


Figure 4.1: Still images from the frozen pond scenario.

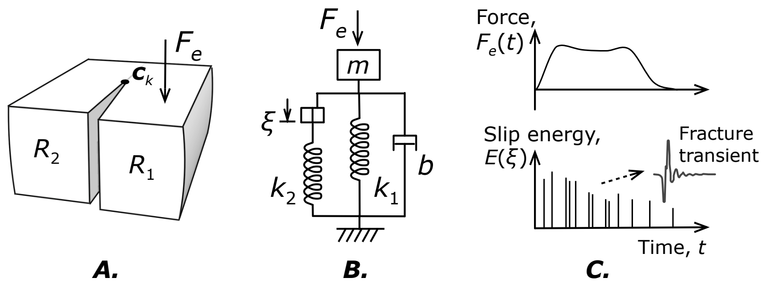


Figure 4.2: *A*. Behavior at the crack front $\mathbf{c}_k$ is modeled from a fracture mechanics perspective. The local volume of ice undergoes shear fracture due to compression. *B*. The response is synthesized by simple mechanical analog. *C*. Each slip event is rendered as an impulsive transient.

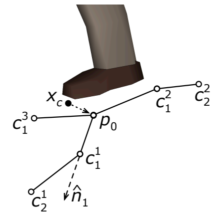


Figure 4.3: Crack patterns, graphs of lines between nodes, $\mathbf{c}_i$.

local temporal crack-growth model given above with heuristics for spatial pattern growth. This allows us to the stringent real-time requirements for audio-vibrotactile feedback. The contact centroid $\mathbf{x}_c$ provides a local summary of the spatial stress injected by the foot. A fracture pattern consists of a collection of crack fronts, defined by linear sequences of node positions, $\mathbf{c}_0, \mathbf{c}_1, \ldots, \mathbf{c}_n$. Fronts originate at seed locations $\mathbf{p} = \mathbf{c}_0$. The fracture is rendered as line primitives $\ell_k = (\mathbf{c}_k - \mathbf{c}_{k-1})$ on the ice sheet (Fig. 4.3).

Seed locations $\mathbf{p}$ are determined by foot-floor contact. A crack event initiated by the audio-tactile process at time t_i with energy $E(t_i)$ results in the creation of a new seed or the growth of fractures from an existing one. A new seed $\mathbf{p}$ is formed at the location of the dominant contact centroid $\mathbf{x}_c$ if no existing seed lies within distance Δp. The new seed $\mathbf{p}$ is created with a random number N_c of latent crack fronts, $\mathbf{c}_0^1, \mathbf{c}_0^2, \ldots \mathbf{c}_0^{N_c}$. We sample N_c uniformly in $2, 3, \ldots 6$, so that the cracks propagate outward from the initial contact position. A crack front propagates from a seed $\mathbf{p}$ nearest to $\mathbf{x}_c$. With probability $1/N_c$ the jth crack front of $\mathbf{p}$ is extended. Its growth is determined by a propagation vector $\mathbf{d}_m^j$ such that $\mathbf{c}_m^j = \mathbf{c}_{m-1}^j + \mathbf{d}_m^j$. We take $\mathbf{d}_m^j = \alpha E \hat{\mathbf{n}}_m^j$, where E is the crack energy, α is a global growth rate parameter, and $\hat{\mathbf{n}}_m^j$ is the direction. Since we lack information about the principal stress directions at the front, we propagate in a direction $\hat{\mathbf{n}}_m^j = \hat{\mathbf{n}}_{m-1}^j + \beta\hat{\mathbf{t}}$, where $\beta \sim N(\beta; 0, \sigma)$ is a Gaussian random variable and $\hat{\mathbf{t}} = \hat{\mathbf{n}}^j \times \hat{\mathbf{u}}$, where $\mathbf{u}$ is the upward surface normal (i.e., $\mathbf{t}$ is a unit vector tangent to $\hat{\mathbf{n}}^j$). The initial directions at $\mathbf{p}$ are spaced equally on the circle.

The method described here is low in cost and complexity, and accessible to multiple users of an interactive floor surface. Despite the promising results, the algorithm may be improved in future work through more accurate simulation of the fracture process. Nonetheless, we believe that these methods hold promise for improving presence during walking in immersive VR and AR environments.

5 Haptic simulation of fluids (INRIA)

INRIA designed a novel approach for 6DoF haptic interaction with viscous fluids using a Smoothed-Particle Hydrodynamics (SPH) physically-based simulation. It allows real-time 6DoF haptic interaction with fluids of variable viscosity through arbitrary shaped rigid bodies. Particularly, fluid containers can be created to hold fluid and hence transmit to the user force feedback coming from fluid stirring, pouring, shaking and scooping, to name a few. Strong forces such as fluid resistance and weight can be captured, as well as light forces such as the inertia of the fluid. Results can be found in a submitted publication which can be found in the private area of `www.niwproject.eu`.

6 The magic barrier tape (INRIA)

INRIA proposed a natural metaphor for locomotion in restricted size workspaces, using real walking in position control when inside the workspace, and an interaction technique in rate control at the limits of the workspace. The main idea is to use a well-known real world object, the barrier tape, and its well-known association to the o not crossessage. The technique visually and clearly defines the workspace where the user can freely walk by surrounding it with virtual barrier tape. When the user reaches the virtual barrier tape, he can move farther in the scene by ushingn the virtual barrier tape. Hence, the technique allows the navigation in an unlimited virtual space, allowing real walking when inside the workspace boundaries, providing an environment safe from collisions with the displays or tracking data loss, and this in a natural and efficient way, without break of immersion. The results can be found in [4].

7 Revisiting Walking-In Place for Desktop Virtual Reality (INRIA)

INRIA has designed a novel Walking-In-Place technique for desktop virtual reality (WP4) based on head movements: the hake-Your-Headechnique.

The Walking-In-Place interaction technique was introduced to navigate infinitely in 3D virtual worlds by walking in place in the real world. The technique has been initially developed for users standing in immersive setups and was built upon sophisticated visual displays and tracking equipments.

In this novel technique, we propose to revisit the whole pipeline of the Walking-In-Place technique to match a larger set of configurations and apply it notably to the context of desktop Virtual Reality. With our novel hake-Your-Headechnique, the user is left with the possibility to sit down, and to use small screens and standard input devices such as a basic webcam for tracking. The locomotion simulation can compute various motions such as turning, jumping and crawling, using as sole input the head movements of the user. We also introduce the use of additional visual feedback based on camera motions to enhance the walking sensations. An experiment was conducted to compare our technique with classical input devices used for navigating in desktop VR. Interestingly, the results showed that our technique could even allow faster navigations when sitting, after a short learning. Our technique was also perceived as more fun and increasing presence, and was generally more appreciated for VR navigation. Results can be found in a related publication accepted at IEEE VRST which can be found in the private area of `www.niwproject.eu`.

8 Conclusions

This deliverable has provided an overview of the different technologies for multimodal simulation developed by the partners of the NIW project. The development of such technologies has been mainly possible thanks to different collaborations between the partners involved in the project. In particular, both UNIVR and AAU have extensively used during the second year the actuator technology developed at UPMC which has been embedded in sandals. INRIA and McGILL have been working on multimodal simulations involving auditory, haptic and visual feedback. The evaluation of such technologies is reported in deliverable 5.1.

References

[1] E. Altinsoy. *Auditory-Tactile interaction in Virtual Environments.* Shaker Verlag, 2006. Web available at `http://www.ias.et.tu-dresden.de/akustik/Mitarbeiter/Altinsoy/data/15.pdf`.

[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] G. Cirio, M. Marchal, T. Regia-Corte, and A. Lécuyer. The magic barrier tape: a novel metaphor for infinite navigation in virtual worlds with a restricted walking workspace. In *Proceedings of the 16th ACM Symposium on Virtual Reality Software and Technology*, pages 155–162. ACM, 2009.

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

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

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

[8] B. L. Giordano, S. McAdams, Y. Visell, J. R. Cooperstock, H. Yao, and V. Hayward. Non-visual identification of walking grounds. In *Proc. of Acoustics'08 in J. Acoust. Soc. Am.*, volume 123 (5), page 3412, 2008.

[9] V. Hayward, G. Dietz, A. Berrezag, N. O. Y. Visell, and J. Cooperstock. Haptic device engineering for walking interactions. Deliverable 2.1, NIW project, 2009. Available at `http://www.niwproject.eu`.

[10] 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.

[11] M. Marchal, A. Lecuyer, G. Cirio, L. Bonnet, and E. M. Walking Up and Down in Immersive Virtual Worlds: Novel Interactive Techniques Based on Visual Feedback. In *Proceedings of IEEE Symposium on 3D User Interface*, 2010.

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

[13] D. Norman. *The Design of Future Things.* Basic Books, New York, 2007.

[14] J. O'Brien and J. Hodgins. Graphical modeling and animation of brittle fracture. In *Proceedings of the 26th annual conference on Computer graphics and interactive techniques*, pages 137–146. ACM Press/Addison-Wesley Publishing Co. New York, NY, USA, 1999.

[15] S. Papetti, F. Fontana, M. Civolani, A. Berrezag, and V. Hayward. Audio-tactile Display of Ground Properties Using Interactive Shoes. *Haptic and Audio Interaction Design*, pages 117–128, 2010.

[16] M. Pauly, R. Keiser, B. Adams, P. Dutré, M. Gross, and L. Guibas. Meshless animation of fracturing solids. *Proceedings of ACM Siggraph 2005*, 24(3):957–964, 2005.

[17] Y. Visell, F. Fontana, B. Giordano, R. Nordahl, S. Serafin, and R. Bresin. Sound design and perception in walking interactions. *Int. J. Human-Computer Studies*, (67):947–959, 2009.

[18] Y. Visell, F. Fontana, B. Giordano, R. Nordahl, S. Serafin, and R. Bresin. Sound design and perception in walking interactions. *International Journal of Human-Computer Studies*, 67(11):947–959, 2009.

[19] Y. Visell, A. Law, S. Smith, J. Ip, R. Rajalingham, and J. Cooperstock. Contact sensing and interaction techniques for a distributed multimodal floor display. In *Proc. of IEEE 3DUI*, 2010.

[20] J. I. S. S. J. R. C. Yon Visell, Alvin Law. Interaction capture in immersive virtual environments via an intelligent floor surface. In *Proc. of IEEE VR*, 2010.