AUDITORY FEEDBACK IN A MULTIMODAL BALANCING TASK: WALKING ON A VIRTUAL PLANK

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ABSTRACT

We describe a multimodal system which exploits the use of footwear-based interaction in virtual environments. We developed a pair of shoes enhanced with pressure sensors, actuators, and markers. Such shoes control a multichannel surround sound system and drive a physically based sound synthesis engine which simulates the act of walking on different surfaces. We present the system in all its components, and explain its ability to simulate natural interactive walking in virtual environments.

The system was used in an experiment whose goal was to assess the ability of subjects to walk blindfolded on a virtual plank. Results show that subjects perform the task slightly better when they are exposed to haptic feedback as opposed to auditory feedback, although no significant differences are measured. The combination of auditory and haptic feedback does not significantly enhances the task performance.

1. INTRODUCTION

In the academic community, foot-based interactions have mostly been concerned with the engineering of locomotion interfaces for virtual environments [1]. A notable exception is the work of Paradiso and coworkers, who pioneered the development of shoes enhanced with sensors, able to capture 16 different parameters such as pressure, orientation, acceleration [2]. Such shoes were used for entertainment purpose as well as for rehabilitation studies [3]. The company Nike has also developed an accelerometer which can be attached to running shoes and connected to an iPod, in such a way that, when a person runs, the iPod tracks and reports different information.

In this paper we mostly focus on enhancing our awareness of auditory and haptic feedback in foot based devices, topic which is still rather unexplored.

We describe a multimodal interactive space which has been developed with the goal of creating audio-haptic-visual simulations of walking-based interactions. The system requires users to walk around a space wearing a pair of shoes enhanced with sensors and actuators. The position of such

shoes is tracked by a motion capture system, and the shoes drive a audio-visual-haptic synthesis engine based on physical models. The idea of enhancing shoes with sensors and actuators is similar to the ones we have been exploring in the context of the Natural Interactive Walking (NIW) FET-Open EU project [1] [7, 8]. The ultimate goal of this project 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 play an important role.

As a case study of the developed architecture, we describe an experiment where subjects were asked to walk straight on a virtual plank. The use of audio-haptic augmented footwear for navigation has not been extensively explored in the research community. An exception are the Cabboots [4], a pair of actuated boots which provide information concerning the shape of a path.

As another example, recently Takeuchi proposed Gilded Gait, a system which changes the perceived physical texture of the ground [5]. The Gilded Gait system is designed as a pair of insoles with vibrotactile feedback to simulate ground textures.

Recently, it has also been demonstrated that walking straight is a hard task also in the physical world. The research was justified by the common belief that people, when getting lost, tend to walk into circles. Subjects were asked to walk straight in two outdoor environments: a forest and a desert. When subjects were not able to see the sun, they walked in circles. It was suggested that veering from a straight course is the result of accumulating noise in the sensorimotor system, which, without an external directional reference to recalibrate the subjective straight ahead [6]. In this paper, we investigate the ability of subjects to walk straight on a narrow virtual plank, with the help of auditory and visual feedback. The results of this research can be applied to the fields of rehabilitation, navigation in virtual and physical worlds as well as entertainment.

2. THE OVERALL ARCHITECTURE

Figure 1 shows a schematic representation of the overall architecture developed. The architecture consists of a motion capture system (MoCap)(Optitrack by Naturalpoint),
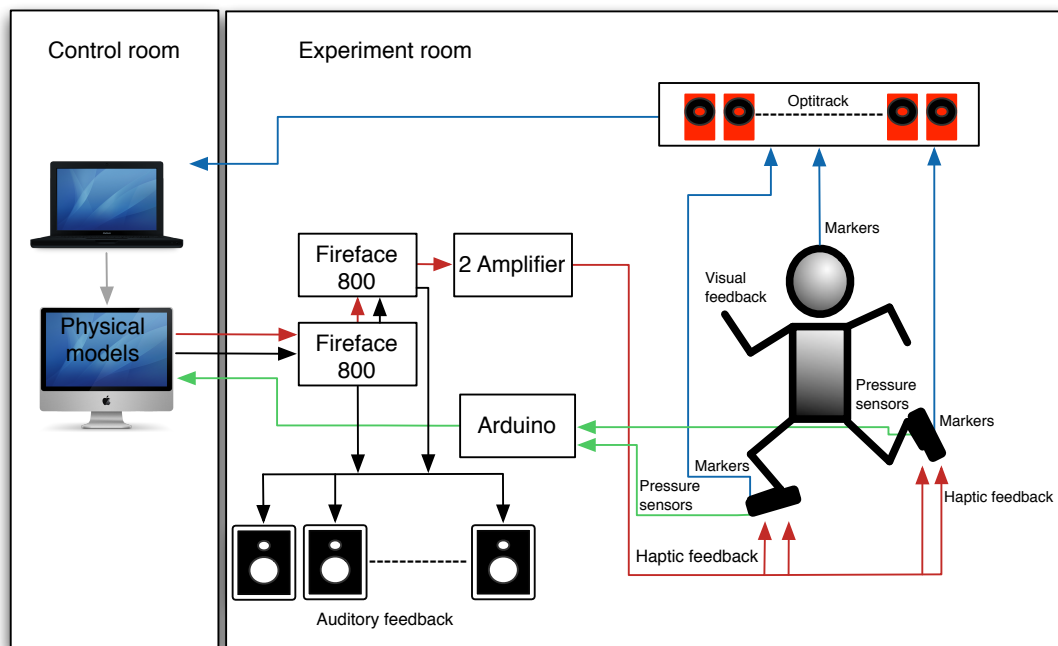
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[1] http://www.niwproject.eu/

Figure 1. A schematic representation of the multimodal architecture to simulate natural interactive walking.

two soundcards (Fireface 800), twelve loudspeakers (Dynaudio), two amplifiers, two haptic shoes and two computers. Such system is placed in an acoustically isolated laboratory which consists of a control room and a larger interaction room where the setup is installed and where the experiments are performed.

The control room is used by the experimenters providing the stimuli and collecting the results. It hosts two desktop computers. The first computer runs the motion capture software[2], while the second runs the audio-haptic synthesis engine. The two computers are connected through an ethernet cable and communicate via UDP. The coordinates relative to the motion capture system are sent from the first to the second computer which processes them in order to control the sound engine.

A transparent glass divides the two rooms, so it is possible for the experimenters to see the users performing the assigned task.

The two rooms are connected by means of a talkback system. The experiment room is 5.45 m large, 5.55 m long, and 2.85 m high, and the walking area available to the users is about $24m^2$.

3. SIMULATION HARDWARE

3.1 Tracking the user

The user locomotion is tracked by an Optitrack motion capture system[3], composed by 16 infrared cameras[4]. The cameras are placed in a configuration optimized for the tracking of the feet and head position simultaneously. In

order to achieve this goal, markers are placed on the top of each shoe worn by the subjects as well as on top of the head.

Users are also tracked by using the pressure sensors embedded in a pair of sandals. Specifically, a pair of lightweight sandals was used (Model Arpenaz-50, Decathlon, Villeneuve d'Ascq, France).

The sole has two FSR pressure sensors[5] whose aim is to detect the pressure force of the feet during the locomotion of a subject wearing the shoes. The two sensors were placed in correspondence to the heel and toe respectively in each shoe. The analogue values of each of these sensors were digitalized by means of an Arduino Diecimila board[6] and were used to drive the audio and haptic synthesis.

3.2 Actuated shoes

In order to provide haptic feedback during the act of walking, a pair of sandals has been recently enhanced with sensors and actuators [9]. The particular model of shoes chosen has light, stiff foam soles that are easy to gouge and fashion. Four cavities were made in the thickness 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, two actuators were placed under the heel of the wearer and the other two under the ball of the foot. These 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

[2] Tracking Tools 2.0 by Naturalpoint
[3] http://naturalpoint.com/optitrack/
[4] OptiTrack FLEX:V100R2

[5] I.E.E. SS-U-N-S-00039
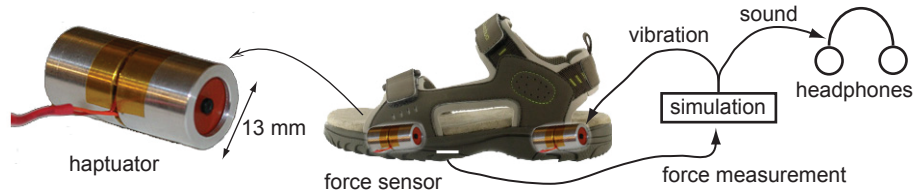[6] http://arduino.cc/

Figure 2. The developed haptic shoes used in this experiment.

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, or to realize other effects such as modulating different, back-front signals during heel-toe movements.

A cable exits from each shoe, with the function of transporting the signals of the pressure sensors and for the actuators. Such cables were about 5 meters long, and they were connected [7] to two 4TP (twisted pair) cables: one 4TP cable carries the sensor signals to a breakout board [8], which then interfaces to an Arduino board; the other 4TP cable carries the actuator signals from a pair of Pyle Pro PCA1 [9] mini 2X15 W stereo amplifiers, driven by outputs from a FireFace 800 soundcard. [10]

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.

In our virtual environment the auditory feedback can be delivered by means of headphones (specifically, Sennheiser HD 650) or a set of 16 channels loudspeakers (Dynaudio BM5A speakers).

4. AUDIO-HAPTIC FEEDBACK

We developed a multimodal synthesis engine able to reproduce auditory and haptic feedback. Auditory feedback is obtained by the combination of a footstep and a soundscape sound synthesis engine. Haptic feedback is provided by means of the haptic shoes previously described. The haptic synthesis is driven by the same engine used for the synthesis of footstep sounds, and is able to simulate the haptic sensation of walking on different surfaces, as illustrated in [9]. The engine for footstep sounds, based on physical models, is able to render the sounds of footsteps both on solid and aggregate surfaces. Several different materials have been simulated, in particular wood, creaking wood, and metal as concerns the solid surfaces, and gravel, snow, sand, dirt, forest underbrush, dry leaves, and high grass as regards the aggregate surfaces. A complete description of such engine in terms of sound design, implementation and control systems is presented in [10]. Using such engine, we implemented a comprehensive collection of footstep sounds. As solid surfaces, we implemented metal, wood, and creaking wood. In these materials, the impact model

was used to simulate the act of walking, while the friction model was used to simulate the creaking sounds typical of creaking wood floors. As aggregate surfaces, we implemented gravel, sand, snow, forest underbrush, dry leaves, pebbles and high grass. The simulated metal, wood and creaking wood surfaces were furthermore enhanced by using some reverberation.

To control the audio-haptic footsteps synthesizer in our virtual environment, we use the haptic shoes: the audio-haptic synthesis is driven interactively during the locomotion of the subject wearing the shoes. The description of the control algorithms based on the analysis of the values of the pressure sensors coming from the haptic shoes can be found [9]. Such engine has been extensively tested by means of several audio and audio-haptic experiments and results can be found in [11] [12] [13] [14].

4.1 Movement to sound mapping

Figure 3 shows the dimensions of the path the users were asked to walk on. The mapping between feet movement and delivered auditory feedback was designed as follows:

- zone 1: a narrow band, 15 cm large and 120 cm long, corresponding to the straight direction to be covered. When both the feet stepped inside this zone, a creaking sound corresponding to the ecological sound of stepping on a creaking plank was provided.

- zones 2 and 3: two narrow bands, 10 cm large and 120 cm long, contiguous to zone 1 and placed at its left and right respectively. When one of the feet was stepping in this zone, no feedback was provided to it. However, subject was still able to continue the task by having the foot move to the correct zone 1. This is analogue to the situation of balancing with only one foot.

- zone 4 and 5: the areas contiguous to zone 2 and 3 and placed at its left and right respectively. When both the feet were inside such zone this was considered as failure for the task, and the recording of a long scream of a person falling down was triggered.

- zone 6: the area in front of zones 1, 2 and 3. When one or both the feet were inside this zone this was considered as success for the task, and the recording of a drum roll with an applause was triggered.

- zone 7: the area beyond of zones 1, 2 and 3. When both the feet were inside this zone, no sound was delivered.

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[7] through DB9 connectors

[8] containing trimmers, that form voltage dividers with the FSRs

[9] http://www.pyleaudio.com/manuals/PCA1.pdf

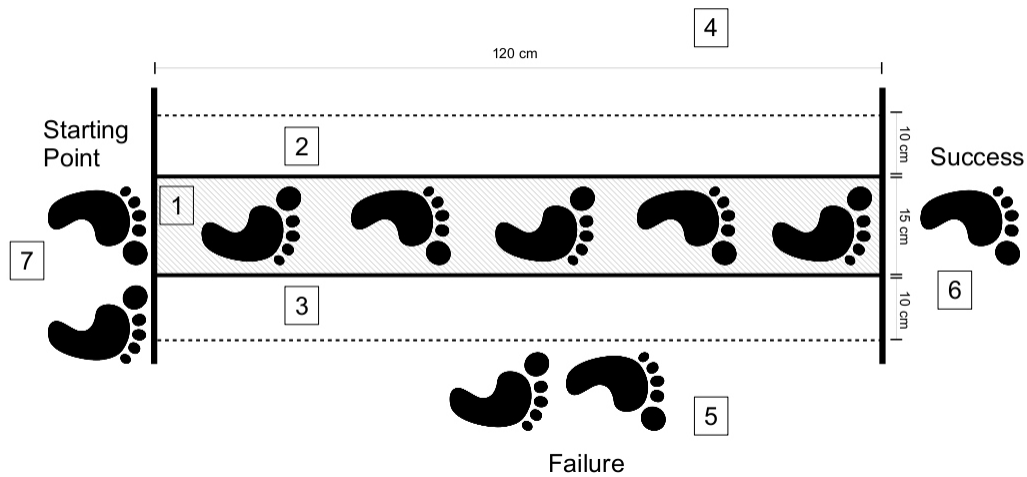[10] http://www.rme-audio.com/english/firewire/ff800.htm

Figure 3. The zones in which the walking space was divided.

5. EXPERIMENT DESIGN

We designed an experiment in order to investigate the role of auditory and haptic feedback in facilitating a balancing task on a virtual plank. In such experiment, we asked subjects to walk straight in order not to virtually fall from the plank. Specifically, subjects were give the following instructions: "Imagine you are walking on a wooden plank. Your task is to walk from one side to the other. Walk slowly and pay attention to the feedback you receive in order to succeed on your task. If your feet are outside of the plank you will fall."

Figure 4 shows a subject performing the experiment. In this particular situation, no visual feedback was provided, and subjects were asked to walk being driven only by auditory and haptic feedback. The same stimuli were provided for the auditory and haptic simulation and designed as follows: when a user is walking on top of the virtual plank, the feet's position is detected by the motion capture system. In this case, the synthesis engine provides as a stimulus the sound and haptic feedback of a creaking wood.

5.1 Participants

The experiment was performed by 15 participants, 14 men and 1 women, aged between 22 and 28 (mean=23.8, standard deviation=1.97). All participants reported normal hearing conditions. The participants took on average 6.8 minutes to complete the experiment.

Subjects were randomly exposed to the four following conditions: auditory feedback, haptic feedback, audio-haptic feedback and no feedback. Each condition was tried twice, given in total eight trials for each subject.

6. RESULTS OF THE EXPERIMENT

Table 1 shows the performance for each subject. The numbers in each row for each conditions indicate whether the subject performed successfully the task ones, twice or never. The results show that feedback helps balance mostly when haptic stimuli are provided. In this case, 46.6% of the tasks
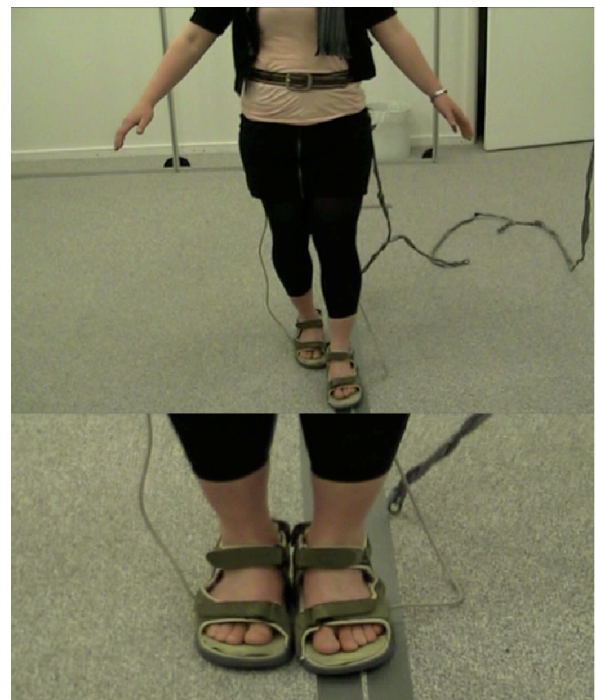

Figure 4. A subject performing the experiment of walking on a virtual plank. The tape on the floor represents the area where the plank is located.

Table 1. Summary of the results of the experiment. The number in each element of the matrix represents the times the task was successful (once, twice or never).

Condition/ Subject number	Audio (A)	Haptic (H)	Audio-haptic (AH)	No-feedback (N)
1	2	1	2	1
2	2	1	1	1
3		1		
4	1	1		
5	1		2	
6	1	1	2	1
7		2	1	
8	1			
9	1	1		
10				
11	1	1		
12		2	1	1
13				
14		1	2	1
15	2	2	1	2

were successfully completed. In the case where a combination of auditory and haptic feedback was provided, 43.3% of the tasks were completed. With only auditory feedback, 40% of the tasks were completed, while with no feedback only 26.6%. These results show how feedback slightly helps the balancing task. Haptic feedback performed better than the combination of auditory and haptic. This can be due to the fact that haptic feedback was provided directly to the feet, so the subjects had a closer spatial connection between the path they had to step on and the corresponding feedback.

A post-experimental questionnaire was also performed, where subjects were asked several questions on the ability to freely move in the environment, to adjust to the technology and to which feedback was the most helpful. Indeed, 7 subjects found the haptic feedback to be the most helpful, 6 subjects the auditory feedback and 2 subjects the combination of auditory and haptic feedback. One subject indeed commented that the most useful feedback was when there was background noise (the pink noise used to mask the auditory feedback) and only vibration was provided. All subjects claimed to notice the relationship between actions performed and feedback provided.

The subjects also commented that the feedback did not always match their expectations, since sometimes no feedback was provided. It is hard to assess if this was due to a technical fault of the system (for example, due to faulty tracking from the motion capture system), or to the fact that subjects were experiencing the condition with no feedback. Some subjects understood that the condition without any feedback was done on purpose, others confused it with a bug of the system.

Some subjects also commented on the fact that shoes were not fitting their size. Moreover, some felt disable without the visual feedback. One subject observed that he simply ignored the feedback and walked straight. This is an indi-

cation of his unwillingness of suspending his disbelief, and behave in a way similar to how they would behave when walking on a real narrow plank [15].

Overall, observations of most of the subjects showed that they were walking carefully listening and feeling the feedback in order to successfully complete the task. It is hard to assess whether the lack of feedback was the condition subjects were exposed to, the fact that they were outside the plank or a fault of the system. Afterall, previous mentioned research has shown that subjects do not walk straight even when they think they do. Some of the test subjects were noticeably not walking straight, although in the post-experimental questionnaire they commented on a faulty system. Very few understood that the lack of feedback was provided intentionally.

7. CONCLUSION

In this paper, we introduced a multimodal architecture whose goal is to simulate natural interactive walking in virtual environments. We present an experiment which assessed the role of auditory and haptic feedback, together with their combination, in helping subjects to complete the task of walking on a virtual rope.

The experiment provided some indications that haptic feedback at the feet level is more useful than auditory feedback when balancing on a virtual plank. Moreover, most subjects behaved in the virtual world as if they would have behaved in the real world, i.e., by walking slowly and carefully to try not to fall from the plank. More experiments, however, are needed to achieve a better understanding of the role of the different modalities in helping navigation and balance control.

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