Inside the Boundaries of the Physical World: Audio-Haptic Feedback as Support for the Navigation in Virtual Environments

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Abstract. One of the main issues in creating virtual environments in a laboratory setting where users can navigate is the fact that laboratories have a limited physical space. One way of compensate this issue has been to redirect users to perform specific paths, keeping for example the illusion of walking straight while indeed subjects were walking in circles. In this paper we investigate whether audio-haptic feedback and haptic feedback alone help in directing users to walk away from the boundaries of a physical space while experimenting with a simulated virtual environment. Specifically, haptic feedback was provided at feet level by using a pair of shoes enhanced with actuators, and auditory feedback of different footsteps was also provided interactively. Results show that it is possible to use auditory and haptic feedback to provide users with navigational cues in virtual environments.

Keywords: walking, audio-haptic feedback, virtual environments.

1 Introduction

One of the main issues encountered when navigating in virtual environments is the fact that the physical limitations of a laboratory prevent users from freely navigate in the virtual world as if they were in the physical world. To cope with such limitations, several approaches have been proposed. As an example, the redirected walking technique proposed in [5] creates a visual illusion where subjects feel as if they were walking straight while instead they are walking in circles. Several variations of such illusion have been exploited, such as redirected walking in place [6], which combines the walking in place technique [15] with redirected walking. The use of haptic feedback at feet level to facilitate navigation is not widely explored in the research community. An exception is the work presented in [2], where an alternative navigation system based on haptic feedback is proposed. Similar work was also presented in [10], where a system that changes the physical texture perceived at the ground is proposed.

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 [9]. This experiment was conducted

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under three different conditions: auditory feedback, haptic feedback, and both. Stimuli were presented to the participants while walking in the laboratory, in such a way to maintain the tight sensorimotor coupling that is natural during walking and foot interaction. This is true for the auditory channel, but even more so for the haptic channel. However, limitations given by the physical space of the laboratory prevented subjects from freely walking as if they were navigating in the real world.

In this paper, we propose a solution to allow subjects to almost freely walk in the real world by providing interactive auditory and haptic feedback. Our hypothesis is that the provided feedback redirects the subjects and drives them inside the boundaries of the physical space. Our system presents several applications related to navigation techniques based on non visual feedback. As an example, the system can allow visual impaired users to be properly directed when navigating in a space with obstacles. This is the case not only for a laboratory setting, but also for navigation in a real world by using a portable version of the system.

2 The Interactive Multimodal System

We recently developed a multimodal interactive architecture with the goal of creating audio-haptic-visual simulations of walking-based interactions [8]. The architecture used during the proposed experiments consists of a motion capture system (MoCap), an head-mounted display (HMD), two soundcards, twelve loudspeakers, an Arduino Diecimila board, two amplifiers, two haptic shoes and two computers (see Figure 1). Users are required to wear a pair of shoes enhanced with sensors and actuators able to provide haptic feedback during the act of walking. In addition, markers are placed on the top of each shoe in correspondence of both heel and toe in order to track the user's locomotion by means of the MoCap. Furthermore, markers are also placed on top of the HMD, in order to track orientation and position of the users' head. Concerning the surround sound system, the configuration of the twelve loudspeakers is illustrated in Figure 2. Eight loudspeakers are placed on the ground at the vertices of a regular octagon, while four loudspeakers are placed in correspondence to the vertices of the the rectangular floor at the height of 1.40 m. All the loudspeakers are used for delivering soundscapes. The eight loudspeakers at floor level are used to deliver footstep sounds. Such configuration was chosen according to the results of preliminary studies on footstep sounds delivery methods.

A multimodal synthesis engine able to reproduce visual, auditory and haptic feedback was also developed on the basis of the architecture described above.

The auditory feedback was obtained by the combination of a footstep and a soundscape sound synthesis engine. The footstep sounds synthesizer used was the one proposed in [14], which allows the real-time simulation of footstep sounds on several different materials. In the proposed experiments, the footstep sounds synthesis was driven interactively during the locomotion of the subject wearing the above mentioned shoes according to the algorithms described in [12].

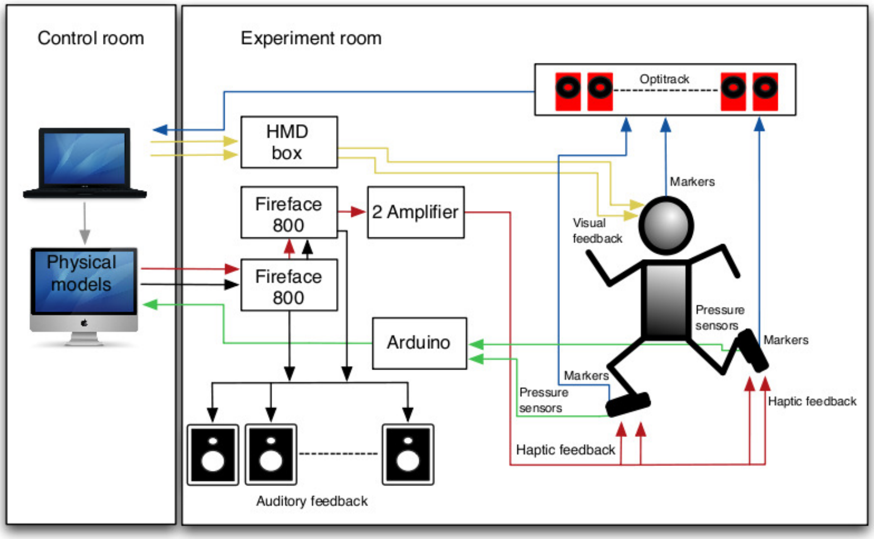

Fig. 1. Schematic representation of the overall architecture developed

During the proposed experiments the footstep sounds were diffused according to a delivery method consisting of the combination of static and dynamic diffusion. For static diffusion we intend that the footstep sounds are diffused simultaneously to the eight loudspeakers using the same amplitude for each loudspeaker. Conversely, during the dynamic diffusion the user position tracked by the MoCap is used to diffuse the footstep sounds according to the vector base amplitude panning algorithm [4] which allows to place under the user's feet the virtual sound source containing the footstep sounds. In this way the sound follows the user trajectories during his/her locomotion, and therefore the eight loudspeakers deliver the footstep sounds with different amplitudes. The approach we followed combines the two methods: the static diffusion was used when the user walked in the central zone of the walking area (see the grey circle in Figure 2), while as soon as the user stepped outside such zone the dynamic diffusion was provided.

As concerns the soundscapes diffusion, the environmental sounds were delivered dynamically using a sound diffusion algorithm based on ambisonics [7].

Regarding the haptic feedback, it was 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 [12].

Concerning the visual feedback provided by the HMD, three outdoor scenarios were developed in order to provide a visual representation of the physically simulated surfaces rendered in the audio-haptic engine. As an example, during the experiments a forest, a snowy landscape and a beach were visually rendered to match the physically simulated forest underbrush, snow and sand.

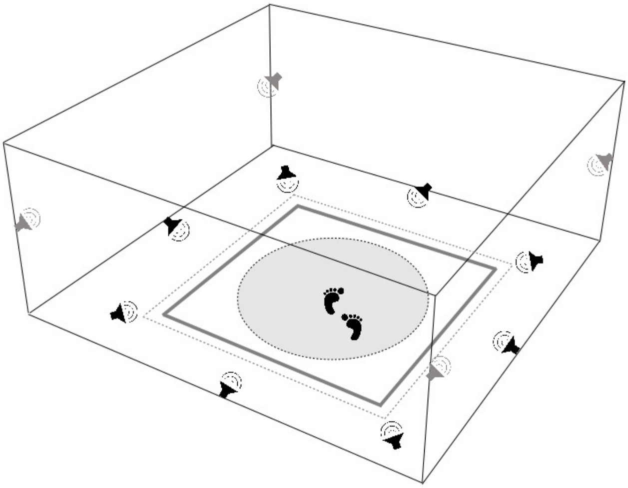

Fig. 2. Loudspeakers' configuration (the 8 loudspeakers used for the footstep sounds diffusion are indicated in black). The area available for the walk is indicated by the rectangular dotted line on the floor. The inner grey rectangle indicates the region inside which the audio-haptic feedback was not changed. The light grey circle indicates the area in which footstep sounds were delivered according to the static diffusion.

3 Method

During the experiments the area of the laboratory available for the users to walk was divided in two zones: an inner zone in which the audio-haptic feedback was not modified ("walking area") and the zone in which the feedback was changed in order to redirect the user inside the walking area. The two zones consisted of two rectangles 2.30x2.40 m and 2.50x2.60 m disposed as indicated in Figure 2 by the grey and the dotted line respectively. The perimeters of both the rectangles were indicated on the floor by means of scotch tape strips. No indications about the boundaries of the walking area were provided at visual level, so the users had to base their walks only on the feedback received sonically and haptically.

Two different techniques were chosen among all the possible methodologies available combining in various ways the auditory and the haptic feedback in order to redirect the walk inside the walking area once one or both the feet had exceeded it:

Method 1: the surface type is changed both at auditory and haptic level
Method 2: the auditory feedback is stopped while the haptic feedback (on the same surface) is kept

In both cases the change of the feedback is provided only in correspondence of the foot which exceeds the boundaries of the walking area. This means that if one foot goes outside the boundary while the other remains inside, the feedback generated by the latter is not affected.

The two approaches were chosen with the aim of being on one hand enough informative and useful for the purpose of warning the walker, and on the other hand intuitive. These choices were made also taking into account the results of previous studies conducted using the haptic shoes and the audio-haptic footsteps synthesizer [13,9]. Such studies revealed on one hand the role of dominance of the auditory feedback on the haptic one, and on the other hand the difficulty in distinguishing at haptic level the surface materials. Therefore the choice of modifying only the haptic feedback would have been not enough informative for the purpose in question. However we did not want to use the auditory feedback alone because the addition of the haptic feedback allows to increase the realism of the interaction [11]. In addition one of the specification requirements was that the change in the feedback had to be as less disruptive as possible for the sensation of the user of being in the virtual environment. As regards the first technique, the audio-haptic change of the surface material was designed in order to avoid the passage from an aggregate surface to a solid one and vice versa (e.g. snow-wood). This in addition would have been perceived by the users as highly incoherent with the surface type visually provided (e.g. a snowy environment). Therefore only materials belonging to the same typology (aggregate-aggregate or solid-solid) were used. Concerning the second technique, the complete stop of the auditory feedback while continuing the haptic one, was chosen because the haptic shoes through the activation of the actuators generate not only the haptic sensation but also a sound having the same nature (but not the same audio quality) of that provided at auditory level. The choice of this design was also supported by the fact that stopping both the auditory and the haptic feedback would have resulted in a too drastic change.

All these considerations led to two hypotheses:

Hypothesis 1: both techniques are informative enough for the task of correctly warning the walker, but the first technique is more helpful compared to the second one

Hypothesis 2: the application of the second technique results as less negatively affecting the sensation of feeling present in the virtual environment compared to the first one

4 Experiment Design

We conducted an experiment whose goal was to assess the limits of the proposed techniques and which of the two was preferred by the users. Each condition of the experiment tested both the two techniques in a different virtual environment: a forest, in condition 1, a snowy landscape in condition 2, and a beach in condition 3. Such scenarios were built in order to fit coherently with the synthesized audio-haptic footsteps on forest underbrush, deep snow and sand respectively.

The reason for choosing three surface materials and three virtual environments was to assess whether the stimulus type affected the quality of the results. Concerning the first technique, the change in the audio-haptic feedback consisted of passing from forest underbrush to gravel, from snow to sand, and from sand to forest underbrush, in the three environments respectively. Conversely in the second technique, the auditory feedback was stopped while the haptic feedback was kept on the same surface.

An experimenter was placed in the room where the experiment was performed by participants, in order to prevent them to fall down because of eventual balance losses as well as in order to take them inside the walking area in case they were not able to follow the audio-haptic cues. The scotch tape lines placed on the floor indicating the two rectangles illustrated in Figure 2 were used by the experimenter to check the participants' behavior in proximity of the boundaries of the walking area.

4.1 Task

During the three conditions participants were asked to wear both the HMD and the haptic shoes previously mentioned and to walk twice in the simulated virtual environment. In each walk one of the two techniques for warning the walker was provided. The order of the techniques was randomized across participants. For each walk the time available to the users lasted two minutes.

Before performing the experiment participants tried both the techniques and were instructed on the task they had to perform. The task consisted of freely navigating the landscape visually provided, modifying the direction of the walk according to the feedback change in order to remain inside the boundaries of the walking area.

Immediately after each walk participants were asked to evaluate (by voice) the following statements on a 9 points Likert scale (1=strongly disagree, 9=strongly agree):

- "The change in feedback made it clear to me that I was leaving the area which I was supposed to stay within."
- "The change in feedback, occurring when I reached the edge of the area which I was supposed to stay within, disrupted the sensation of being there in the virtual environment."

At the end of the two walks participants were asked to answer to the following questions in order to compare the two techniques:

- "Which of the two feedback types made it the easiest to determine that you had reached the edge of the area which you were supposed to stay within?"
- "Which of the two feedback types was the least disruptive for your sensation of being there in the virtual environment?"

Finally at the end of the experiment subjects were asked to evaluate the system they interacted with, by means of a questionnaire built on the Virtual Experience Test (VET) proposed in [1]. Such survey aims to measure holistic virtual environment experiences based upon five dimensions of experiential design: sensory, cognitive, affective, active, and relational. Nevertheless only the questions relative to the sensory and cognitive dimensions were utilised since our main goal was not to measure the presence level experienced by participants. Rather we were interested on one hand in their evaluations of the sensory hardware and content quality, as well as of the consistency of the sensory information, and on the other hand in the ratings of their perceived ability to complete the proposed task and to understand the environments rules.

The utilized questions are illustrated in section 5.1, and were evaluated on a 9 points Likert scale (1=strongly disagree, 9=strongly agree). The order of the questions was randomized using a 5x5 Latin square to reduce questionnaire order bias. Finally, participants were also given the opportunity to leave an open comment on their experience interacting with the system.

4.2 Participants

Thirty participants were divided in three groups ($n = 10$) to perform the experiment. The three groups were composed respectively of 8 men and 2 women, aged between 24 and 33 (mean=26.08, standard deviation=3.08), 8 men and 2 women, aged between 23 and 35 (mean=27.8, standard deviation=4.56), and 8 men and 2 women, aged between 20 and 30 (mean=23.3, standard deviation=2.83). Participants took on average about 6 minutes to complete the walking experiment, and about 5 minutes to complete the questionnaire. All participants reported normal hearing conditions and no locomotion problems.

5 Results

The collected answers were analyzed and compared between the three conditions. Results are illustrated in Table 1. The first noticeable element emerging from these data is that the first technique led to a higher number of successful completion of the task (i.e. participants correctly understood the warning and therefore moved back inside the walking area) and a lower number of unsuccesses compared to the second technique. An in-depth analysis using chi-square test, shows significant difference between the two conditions ($\chi^2(1) = 25.05$, $p < 0.001$).

Considering the total number of successes and unsuccesses it is possible to notice that participants reached the boundaries of the walking area an amount of times greater during the use of the first technique compared to when the second technique was presented.

Furthermore the total number of successes and unsuccesses of both the techniques, was higher for the forest environment rather than the other two, as well as for beach respect to the snowy landscape. The statistical analysis conducted by means of a t-test revealed significant differences for forest compared to snowy landscape ($t(38) = 3.628$, $p < 0.001$) and for sand compared to snowy landscape ($t(38) = 3.106$, $p = 0.003$). As regards the evaluation of the clearness of the feedback in providing the information on which direction taking in order to stay within the walking area, the average scores are always higher for the first technique. The statistical analysis conducted by means of a t-test revealed that such differences are significant (t(58) = 2.418, p = 0.019). As concerns the evaluations of the level of presence disruption, higher evaluations were given for the second technique in two cases out of three, with the exception of the beach environment (overall no significant difference was measured).

Concerning the preferences expressed by participants after having tried both the techniques, it is possible to notice that the first technique was clearly preferred to the second one. Indeed the first technique was found more useful and intuitive than the second one, as well as less disruptive for the presence level (with the exception of the beach environment, for which the percentages are identical). In addition an exact binomial test revealed that the preferences for the technique 1 are significant (p = 0.001 in the first case and p = 0.042 in the second one).

Table 1. Results of the experiment

	Forest		**Snow**		**Beach**	
	Technique 1	Technique 2	Technique 1	Technique 2	Technique 1	Technique 2
Number of successes	70	42	48	32	59	29
Number of unsuccesses	17	28	16	25	20	37
Total number of successes/unsucesses	87	70	64	57	79	66
Clearness	7.9 ± 0.87	6.1 ± 2.55	7.5 ± 1.77	7.2 ± 1.61	6.9 ± 1.8	5.3 ± 2.45
Presence disruption	3.8 ± 2.48	4.2 ± 2.29	5.7 ± 2	6.1 ± 2.33	5 ± 2.26	4.3 ± 2.35
Preference easiest	90%	10%	70%	30%	80%	20%
Preference least disruptive	80%	20%	80%	20%	50%	50%

5.1 System Evaluation

As mentioned in section 4.1, at the end of the experiment participants were provided with a questionnaire in order to evaluate the system they interacted with. Results are shown in Table 2; questions from Q1 to Q7 are relative to the sensory experimental design dimension, while questions from Q8 to Q11 concern the cognitive one.

As regards the sensory input (visual, aural, and haptic), as well as the perception of those stimuli, it is possible to notice that there are not very high evaluations for the investigated parameters. This can be seen as an indication of a lack in the utilized technology for both the sensory hardware and software that create the sensations. Even if the evaluations are never low, the questionnaire results points toward an improvement of the system technology. Negative correlation was found between the evaluations of the questions Q1, Q3, and Q5 relative to the hardware and the questions Q2, Q4, and Q6 relative to the provided content.

As concerns the cognitive dimension, the evaluations about how well the environment supported task engagement through the clarity of task explanations, the perceived task interest and the explanation of environment rules, are mostly around average. However these data are relative to the tasks conducted with both the techniques, therefore the interpretation of such result should take into account the fact that while the first technique was well understood, for the second one the participants' performances were less successful.

Overall, almost always the average scores for both the sensory and the cognitive dimensions, are higher for the snowy landscape compared to the other two, revealing that the best interaction occurred with that virtual environment.

Table 2. Results of the questionnaire on the system

Questions	**Forest**	**Snow**	**Beach**
Q1: I found the visual display hardware to be of high quality	4.4 ± 2.1	5.8 ± 1.3	5.4 ± 2.1
Q2: I found the visual content of the environment to be of high quality	4.6 ±1.9	6.1 ± 1.4	5.1 ± 1.8
Q3: I found the audio hardware to be of high quality	6.1 ± 1.6	6.8 ± 1.1	4.6 ± 1.9
Q4: I found the audio content of the environment to be of high quality	6 ± 1	7.1 ± 0.8	5.3 ± 1.8
Q5: I found the haptic hardware to be of high quality	4.3 ± 1.8	6.4 ± 2.3	4.1 ± 1.5
Q6: I found the haptic content of the environment to be of high quality	4.9 ± 2	5.6 ± 2	3.6 ± 1.6
Q7: I found that the sensory information of the virtual environment was consistent	5.5 ± 2.1	6.1 ± 2.4	5.4 ± 2.5
Q8: I found that the content in the virtual environment was helpful in informing me of my current task	4.8 ± 2	4.2 ± 2.8	4 ± 2.3
Q9: I found the user interface to be helpful in informing me of my current task	4 ± 2.2	5.4 ± 2.6	5 ± 1.5
Q10: I thought that the virtual environment made it clear what I was and was not allowed to do	4 ± 1.8	4.4 ± 3.2	3.8 ± 1.9
Q11: I thought that the tasks I was able to do in the virtual environment were interesting	3.4 ± 1.9	4.2 ± 2.5	5.1 ± 2.5

6 Discussion

The results of the experiment are clear: the participants' performances were better with the first technique, and participants preferred it to the second one. Our initial hypotheses were only partially confirmed. Indeed on one hand only the first technique led to a correct warning of the walker in most of the cases, while the second technique presented a too high number of unsuccesses compared to the successful completion of the task. On the other hand, the second technique was also rated as the more negatively affecting the sensation of feeling present in the virtual environment compared to the first one.

A deeper observation of the participants' performances revealed that also the second technique proved to work well. Indeed most of the successful completion happened towards the end of the task, indicating that participants needed a learning phase longer than the one they tried at the beginning of the experiment. Moreover, this aspect was reported in the comments of some participants. However one of the participants also reported that in presence of the second technique he was satisfied of the proposed feedback since the continuous presence of the haptic allowed to mask the sensation of walking on a laboratory surface therefore increasing the realism of his interaction.

Concerning the performances at the moment of reaching the boundaries, for the second technique it was observed a delay in the choice of which direction to take in order to come back inside the walking area: participants took longer time to realize where they had to place the next step compared to the first technique. Furthermore, it was noticed that while for the first technique rarely participants placed both the feet outside the walking area before correctly coming back, this instead happened more frequently for the second technique. As regards the negative effect of the techniques on sense of presence, it is not possible to conclude that the first technique was significantly perceived as the less disruptive. However, results seem to point toward this direction since in two cases out of three the first technique was preferred and rated as the best one from this point of view. Nevertheless, evaluations of the presence disruption parameter of Table 1 are not low neither for the first technique, revealing that the impact of the use of the proposed techniques on the presence level is still too high.

An unexpected result of this research was that the the total number of successes and unsuccesses of both the techniques, was quite different between the three virtual environments. Indeed it was higher for the forest environment rather than the other two, as well as for beach respect to the snowy landscape. This is an indication that the average quantity of motion was different in the three simulations. In addition, a difference in the gaits was also observed: participants tended to walk more and faster in the forest environment rather than the other two, while the lowest average velocity was held during the navigation of the snowy landscape where in addition some of the participants tended to remain stopped, exploring visually the environment rather than by walking. On one hand this result seems to be related to the fact that participants felt present in the virtual environment they were exploring; on the other hand the noticed differences in the gaits could also be related to the different degrees of compliance of the three surfaces simulated at auditory and haptic level.

As concerns the system evaluation, it emerges the necessity of improvements of the system technology both at software and hardware level. In particular for a better experience while physically navigating the simulated virtual environment it would be needed a totally wireless system; indeed the wires of the HMD as well as those coming out from the haptic shoes limit a lot the freedom of the navigation and in some cases the participants became aware of this aspect during the interaction with the environment. Improving these aspects would allow also to increase the presence level experienced by users, since the quality of sensory hardware, as well as the sensory content, has a widespread positive effect on reported presence, as shown in a review done by [3].

7 Conclusion

In this study two techniques for warning walkers were proposed and evaluated. The first technique consisted of the change of the surface type both at auditory and haptic level; the second one consisted in the stop of the auditory feedback only, while the haptic feedback continued on the same surface.

Results show that by means of the proposed techniques it is possible to navigate a walker inside the walking area once one or both the feet had exceeded it, even if the first technique produced better performances and was preferred by participants. However, results also show that the use of these techniques produced a not negligible disruption of the sense of presence.

An unexpected results of the proposed study was that the quantity of motion produced during participants' navigations was different in the three simulated environments. This aspect could be related to the type of the simulated surface and deserves to be investigated in a deeper way.

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