FP7-ICT-2007-C
Objective ICT-2007.8.0
FET-Open 222107

NIW
Natural Interactive Walking

Deliverable 7.2

PANEL ON FOOT BASED INTERFACES AND INTERACTIONS

Sep. 23, 2011
v. 1.0

Classification: PU

Contents

0.1 Introduction

The goal of this deliverable is to report on a special session which was organized as part of the Haptic-Audio Interaction Design (HAID 2010) conference which took place at Aalborg University in Copenhagen on September 17th, 2010.

The session was entitled "Walking and navigation interfaces" and was chaired by Federico Fontana, the coordinator of the NIW project.

The papers presented in this session are included in this document. The section was organized as follows:

- 10:15 10:35 Turchet, Serafin, Dimitrov and Nordahl. Conflicting audio-haptic feedback in physically based simulation of walking sounds.
- 10.35 11.20 Coffee break (around posters)
- 11:20 11:40 Magnusson, Rassmus-Grohn and Szymczak. The influence of angle size in navigation applications using pointing gestures.
- 11.40 12.00 Papetti, Fontana, Civolani, Berrezag and Hayward. Audio-Tactile Display of Ground Properties Using Interactive Shoes.
- 12.00 12.20 Civolani, Fontana, Papetti. Efficient Acquisition of Force Data in Interactive Shoe Designs.
- 12.20 12.40 Srikulwong and O Neill. A Comparison of Two Wearable Tactile Interfaces with a Complementary Display in Two Orientations.

As can be seen from the papers presented, three out of the four presentations were delivered by researchers involved in the NIW project. This gave us an opportunity to promote NIW to the community of audio and haptic interaction design. The other papers were related to topics of interest for NIW.

0.2 Included papers

Conflicting Audio-haptic Feedback in Physically Based Simulation of Walking Sounds

Luca Turchet, Stefania Serafin, Smilen Dimitrov, and Rolf Nordahl

Medialogy, Aalborg University Copenhagen
Lautrupvang 15, 2750 Ballerup, DK
{tur,sts,sd,rn}@media.aau.dk

Abstract. We describe an audio-haptic experiment conducted using a system which simulates in real-time the auditory and haptic sensation of walking on different surfaces. The system is based on physical models, that drive both the haptic and audio synthesizers, and a pair of shoes enhanced with sensors and actuators. Such experiment was run to examine the ability of subjects to recognize the different surfaces with both coherent and incoherent audio-haptic stimuli. Results show that in this kind of tasks the auditory modality is dominant on the haptic one.

1 Introduction

While several studies have investigated the interaction between touch and audition in hand based interactions, to our knowledge, the interaction of auditory and haptic feedback in foot based devices is still an unexplored topic.

A notable exception is the work of Giordano et al., who showed that the feet were also effective at probing the world with discriminative touch, with and without access to auditory information. Their results suggested that integration of foot-haptic and auditory information does follow simple integration rules [1].

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

In particular, the results indicated that subjects were able to recognize most of the stimuli in the audition only condition, and some of the material properties such as hardness in the haptics only condition. Nevertheless, the combination of auditory and haptic cues did not significantly improve recognition.

In a successive research we extended that work improving the developed technology which allowed subjects to walk in a controlled laboratory, where their

R. Nordahl et al. (Eds.): HAID 2010, LNCS 6306, pp. 97–106, 2010.

steps were tracked and used to drive the simulation [4]. Overall, results showed that subjects were able to recognize most of the synthesized surfaces with high accuracy. Results moreover confirmed that auditory modality is dominant on the haptic modality and that the haptic task was more difficult than the other two. Indeed such results showed that subjects performed the recognition task better when using auditory feedback versus haptic feedback, and that the combination of auditory and haptic feedback only in some conditions significantly enhanced the recognition.

Starting from those results, in this paper we investigate in a deeper way the role of dominance of the two modalities involved by means of a preliminary discrimination experiment. In particular, while in previous research we focused on providing coherent stimuli in the auditory and haptic modality, here we provide conflicting stimuli, to understand which modality is dominant.

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

2 Simulation Hardware and Software

We developed a system which simulates in real-time the auditory and haptic sensation of walking on different surfaces. A schematic representation of this system is shown in Figure 1. In order to provide both audio and haptic feedback, haptic shoes enhanced with pressure sensors have been developed. The way pressure sensors and actuators are embedded in the sandals can be seen in Figure 2, and a picture of a user wearing the shoes is shown in Figure 3. A complete description of such system and of all its components is given elsewhere in detail [5].

The hardware allows to control in real-time of a sound synthesis engine based on physical models. Such engine is illustrated in our previous research [3,7,6]. The same physical models have been used to drive the haptic and the audio synthesis.

As mentioned in section 1, the system has been evaluated by using it both offline and interactively. The complete results of this evaluation are described in [2,4].

3 Experiment

We conducted an experiment whose goal was to investigate the role of dominance of the audio and haptic modalities during the use of our walking system. Subjects were asked to interact with the system and to recognize the different walking sounds and vibrations they were exposed to.

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

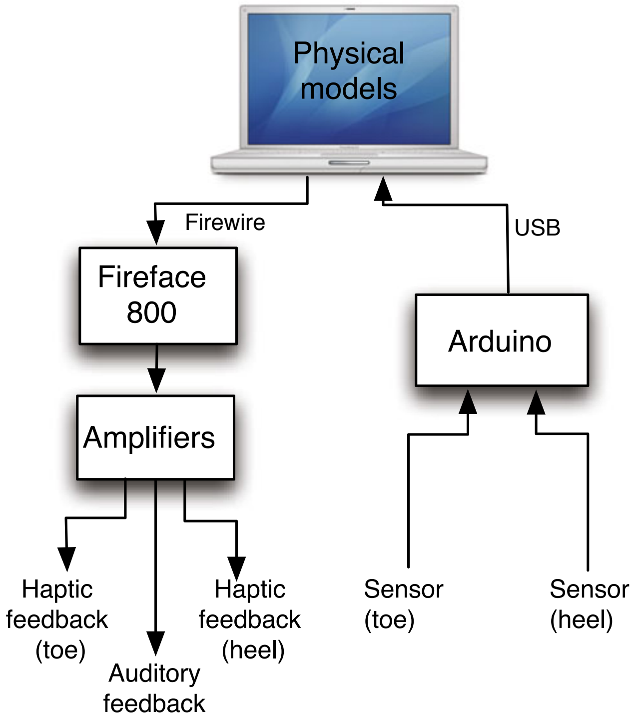


Fig. 1. Diagram illustrating the different hardware components of the system, together with their connections to the PC. The representation is for one shoe.

The experiment consisted of both coherent and incoherent audio-haptic stimuli. In presence of coherent stimuli the same surface material was presented both at audio and haptic level. Instead the provided incoherent stimuli consisted of different surface materials; in particular when at audio level a solid surface was presented, at haptic level an aggregate surface was modeled, and viceversa.

One of our hypotheses was that the audio modality would have dominated the haptic one. Another was that the recognition would have slightly improved using coherent stimuli rather than the incoherent ones. Similarly we hypothesized higher evaluations in terms of realism and quality in presence of coherent stimuli.

3.1 Participants

Ten participants, 7 male and 3 female, aged between 20 and 38 (mean = 25.81, standard deviation = 5.77), were involved in the experiment.

All participants reported normal hearing conditions and all of them were naive with respect to the experimental setup and to the purpose of the experiment.

The participants took on average about 11 minutes to complete the experiment.

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

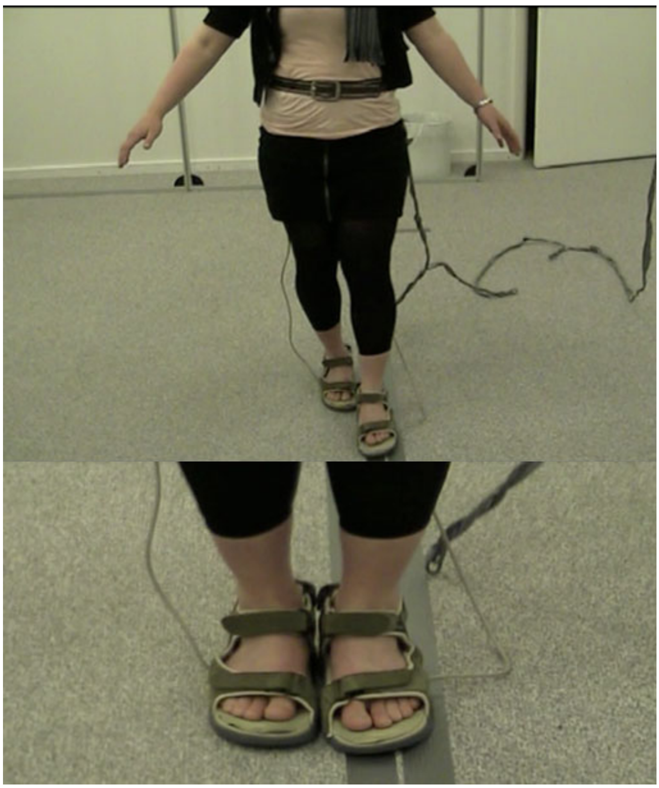


Fig. 3. Top: A user wearing the sandals enhanced with sensors and actuators. Bottom: the sandals.

3.2 Setup

The experiment was carried out in an acoustically isolated laboratory. The walking area was approximately 18 square meters, delimited by the walls of the laboratory.

The setup consisted of the pair of sandals mentioned in section 2, an Arduino board, a Fireface soundcard, a laptop and a set of headphones[2]. In order to facilitate the navigation of the subjects, the wires coming out from the shoes in all setups, as well as the wires connecting the headphones to the soundcard, were linked to a bumbag or to snaplinks attached to trousers.

3.3 Task

During the experiment participants were asked to wear the pair of sandals and the headphones described in sections 2 and 3.2, and to walk in the laboratory.

During the act of walking they listened simultaneously to footsteps sounds and vibrations on a different surface according to the stimulus presented. The task consisted of answering, by writing on a paper, the following three questions after the presentation of the stimulus:

1. Which surface do you think you are walking on? For each stimulus choose a material.
2. How close to real life is the sound in comparison with the surface you think it is? Evaluate the degree of realism on a scale from 1 to 7 (1=low realism, 7=high realism).
3. Evaluate the quality of the sound on a scale from 1 to 7 (1=low quality, 7=high quality).

As opposed to our previous research, participants were not provided with a forced list of possible choices. This was due to the fact that we wanted subjects to be somehow creative in their recognition of the surface, without guessing from a predefined list.

Subjects were informed that they could use the interactive system as much as they wanted before giving an answer. They were also told that they could choose the same material more than one time. When passed to the next stimulus they could not change the answer to the previous stimuli.

At the conclusion of the experiment, participants were asked some questions concerning the naturalness of the interaction with the system and to comment on its usability and possible integration in a virtual reality environment. In particular the questionnaire was the following:

– Imagine that this is part of a system used to navigate in a computer game, answer to the following questions:
    1. How natural is the interaction? Evaluate on a scale from 1 to 7 (1=little natural, 7=very natural)

[2] Sennheiser HD 600, http://www.sennheiser.com

2. How normal do you feel during the act of walking? Evaluate on a scale from 1 to 7 (1=little normal, 7=very normal)
3. How constrained do you feel during the act of walking? Evaluate on a scale from 1 to 7 (1=little constrained, 7=very constrained)

In addition they were also given the opportunity to leave an open comment on their experience interacting with the system.

3.4 Experimental Plan

Participants were exposed to 12 trials consisting of 4 coherent stimuli and 8 incoherent stimuli. The 12 audio-haptic stimuli were presented once in randomized order.

The modeled surfaces were 4 (2 solid and 2 aggregate): wood, metal, snow and gravel. In presence of incoherent stimuli the conflict was rendered providing on the one hand one of the solid surfaces by means of auditory feedback, while at haptic level one of the aggregate surfaces was presented. On the other hand, analogously, another set of incoherent stimuli consisted of aggregate surfaces at auditory level while a solid surface was presented by means of haptic feedback.

4 Results and Discussion

Table 1 shows the confusion matrix resulting from the experiment. In such table are illustrated the participants answers gathered according to three material categories: solid, aggregate and liquid.

The first noticeable element emerging from the table is that none of the participants classified as liquid the simulated surfaces. Moreover it is very evident that in presence of conflicts the auditory modality is strongly dominant on the haptic one. This result is more clearly illustrated in table 2, and it seems to be confirmed by the answers concerning the names of the chosen materials (see table 3). Indeed, participants had the tendency to answer with the same names chosen when a same material was presented at auditory level both in presence of coherent and incoherent stimuli. In other words they were driven in their choice by the auditory feedback.

This does not mean that they completely ignored the haptic part of the bimodal stimulus; indeed in the comments two participants reported that they noticed that only some of the haptic stimuli where appropriate for the sound they were listening. Moreover results show that in two cases participants seemed to be driven in their choices, at least partially, by the haptic feedback; this is the case of the audio-haptic stimulus metal-snow for which one participant surprisingly gave the answer “mud” which can be considered appropriate for the haptic stimulus. Concerning the stimulus snow-wood one participant chose the answer “carpet” which seems to consider both the two components of the bimodal stimulus since the sound of snow could be interpreted as the sound on carpet in presence of an haptic feedback expressing a solid surface like wood. Both the participants, like all the others, were asked, at the conclusion of the experiment,

Table 1. Confusion matrix of experiment

Stimulus		Answer			
Audio	**Haptic**	**Solid**	**Aggregate**	**Liquid**	**I don't know**
Wood	Wood	7	1		2
Wood	Snow	7			3
Wood	Gravel	6	1		3
Metal	Metal	9			1
Metal	Snow	6	1		3
Metal	Gravel	8			2
Gravel	Gravel		9		1
Gravel	Wood		10		
Gravel	Metal		7		3
Snow	Snow		10		
Snow	Wood		9	1	
Snow	Metal		9		1

Table 2. Percentages of dominance of the auditory and haptic modalities in presence of incoherent stimuli

Stimulus		Dominance	
Audio	**Haptic**	**% Audio**	**% Haptic**
Wood	Snow	70	0
Wood	Gravel	60	0
Metal	Snow	60	10
Metal	Gravel	80	0
Gravel	Wood	100	0
Gravel	Metal	70	0
Snow	Wood	90	10
Snow	Metal	90	0

to explain their answers and they confirmed their choices. In particular all the participants were asked at the end of the experiment to classify their answers as belonging to the categories of solid, aggregate or liquid materials.

For the stimulus wood-gravel one participant reported the answer "not solid plastic" which could be addressed as haptic dominance, but the same participant chose the same answer also for the coherent stimulus wood-wood and for this reason we did not consider such answer as haptic dominance in table 2.

Regarding the percentages of "I don't know" answers, although the number is low, it is an indication of the difficulty of the proposed task. This fact was also confirmed in numerous comments left by participants who on average reported that the task was very difficult. Although the comparison between coherent and incoherent stimuli with the same auditory stimulus do not reveal any statistically significant difference (confirming from another point of view the dominance of the auditory feedback), the percentages of "I don't know" answers is on average higher for the incoherent stimuli.

Table 3. Names of the materials chosen for each audio-haptic stimulus. In bold the choices which seem to be driven by the haptic feedback.

Stimulus		**Answer**
Audio	**Haptic**	**Names of chosen materials**
Wood	Wood	wood, concrete, plastic, not solid plastic
Wood	Snow	wood, concrete, plastic, gum
Wood	Gravel	wood, concrete, plastic, not solid plastic
Metal	Metal	metal, iron, steel, wood, glass
Metal	Snow	metal, iron, steel, wood, glass, **mud**
Metal	Gravel	metal, iron, steel, wood, glass, plastic
Gravel	Gravel	gravel, little stones, sand
Gravel	Wood	gravel, little stones, sand
Gravel	Metal	gravel, little stones, sand
Snow	Snow	snow, ice, gravel, sand, leaves, not solid plastic, paper
Snow	Wood	snow, ice, gravel, sand, leaves, not solid plastic, **carpet**
Snow	Metal	snow, ice, gravel, sand, not solid plastic

Table 4. Average realism and quality scores from a seven-point Likert scale and relative standard deviation

Stimulus		**Realism**		**Quality**	
Audio	**Haptic**	μ	σ	μ	σ
Wood	Wood	2.75	1.488	3.25	1.2817
Wood	Snow	2.7143	1.496	3.2857	1.2536
Wood	Gravel	2.5714	1.8127	2.7143	1.3801
Metal	Metal	2.8889	1.6159	4	2
Metal	Snow	3.8571	1.496	3.5714	1.1339
Metal	Gravel	2.625	1.3025	2.875	1.5526
Gravel	Gravel	3.2222	1.0929	4	1
Gravel	Wood	4	0.9428	4.4	0.9661
Gravel	Metal	3.7143	1.8898	4.1429	1.4639
Snow	Snow	3.7	1.567	3.8	1.3984
Snow	Wood	3.6	1.4298	3.7	1.567
Snow	Metal	4	1.5	4.1111	1.453

Table 5. Questionnaire results. Average scores from a seven-point Likert scale and relative standard deviation.

	μ	σ
Naturalness	3.5	1.6499
Normality	4	1.5635
Constriction	4.2	1.3166

Table 4 shows the degree to which participants judged the realism and the quality of the experience. Such parameters were calculated by looking only at the answers different from "I dont know". Contrary to our hypotheses we did not find higher evaluations of these parameters for the coherent stimuli compared to the incoherent one. Surprisingly for some stimuli the evaluations are even higher for the incoherent stimuli. Anyways an in depth statistical analysis performed with the t-test revealed that all these differences are not significative.

Finally, as concerns the questionnaire conducted at the conclusion of the experiment, results in table 5 show that that subjects judged the interaction with the system not too much natural (mean = 3.5), and that they felt quite normal (mean = 4) but at the same time quite constrained (mean = 4.2) during the act of walking.

Indeed, more than one subject commented on the need of a wireless system able to convey vibrations to the shoes and sounds to the headphones set.

5 Conclusion and Future Work

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

In the experiment, both coherent and incoherent audio-haptic stimuli were provided. Results confirm that auditory modality is dominant on the haptic one. This can be due to the low sensitivity of the foot when exposed to haptic signals.

The developed system is ready to be integrated in computer games and interactive installations where a user can navigate.

In future work, we indeed plan to utilize the system in multimodal environments, and include visual feedback, to understand the role of the different sensorial modalities to enhance sense of immersion and presence in scenarios where walking plays an important role.

Acknowledgment

The research leading to these results has received funding from the European Community's Seventh Framework Programme under FET-Open grant agreement 222107 NIW - Natural Interactive Walking.[3] The authors wish also to thank Amir Berrezag and Vincent Hayward who provided the shoes used in the experiments.

References

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

[3] www.niwproject.eu

2. Nordahl, R., Berrezag, A., Dimitrov, S., Turchet, L., Hayward, V., Serafin, S.: Preliminary experiment combining virtual reality haptic shoes and audio synthesis. In: Proc. Eurohaptics (2010)
3. Nordahl, R., Serafin, S., Turchet, L.: Sound synthesis and evaluation of interactive footsteps for virtual reality applications. In: Proc. IEEE VR 2010 (2010)
4. Serafin, S., Turchet, L., Nordahl, R., Dimitrov, S., Berrezag, A., Hayward, V.: Identification of virtual grounds using virtual reality haptic shoes and sound synthesis. In: Proc. of Eurohaptics Symposium on Haptics and Audio-Visual Environments (2010)
5. Turchet, L., Nordahl, R., Berrezag, A., Dimitrov, S., Hayward, V., Serafin, S.: Audio-haptic physically based simulation of walking sounds. In: Proc. of IEEE International Workshop on Multimedia Signal Processing (2010)
6. Turchet, L., Nordahl, R., Serafin, S.: Examining the role of context in the recognition of walking sounds. In: Proc. of Sound and Music Computing Conference (2010)
7. Turchet, L., Serafin, S., Dimitrov, S., Nordahl, R.: Physically based sound synthesis and control of footsteps sounds. In: Proceedings of Digital Audio Effects Conference (2010)

The influence of angle size in navigation applications using pointing gestures

Charlotte Magnusson[1], Kirsten Rassmus-Gröhn[1], Delphine Szymczak[1]

[1]Department of Design Sciences, Lund University, Box 118,
221 00 Lund, Sweden
{charlotte, kirre, delphine.szymczak}@certec.lth.se

Abstract. One factor which can be expected to influence performance in applications where the user points a device in some direction to obtain information is the angle interval in which the user gets feedback. The present study was performed in order to get a better understanding of the influence of this angle interval on navigation performance, gestures and strategies in a more realistic outdoor setting. Results indicate that users are able to handle quite a wide range of angle intervals, although there are differences between narrow and wide intervals. We observe different gestures and strategies used by the users and provide some recommendations on suitable angle intervals. Finally, our observations support the notion that using this type of pointing gesture for navigation is intuitive and easy to use.

Keywords: Non-visual, pointing, gesture, audio, mobile, location based

1 Introduction and related work

The introduction of compasses in more and more hand held devices has opened the way for applications making use of pointing gestures to provide information about objects or locations in the real world. With geo tagged information on a device which knows where it is (through GPS or other means) and also knows in which direction it is pointing (through a compass) it is possible to show the user information on important buildings, restaurants, future or past events etc etc in the direction the device is pointing (http://layar.com). Using non-speech sound or vibration in a handheld device to guide pedestrians in a wayfinding situation has been studied previously but not extensively. One group of proof-of-concept systems make use of spatial audio for navigation purposes and thus require headphones. AudioGPS by Holland et al. [1] displays the direction and the distance to a target uses stereo together with a repeated fixed pitch tone and a repeated varying pitch tone to give the user the directional information. A Geiger counter metaphor is used to convey distance from target (more frequent tone bursts the closer to the target the user is). In gpsTunes created by Strachan et al. [2] the user's preferred music was placed with spatial audio to provide bearing and distance information. As long as the user kept walking in the direction of the goal, the music was played at the desired volume. Stahl's The Roaring Navigator [3] guides visitors at a zoo by playing the sounds of the three nearest animals. The system also uses speech recognition for interaction and speech to display further information about the animals to the user. Jones et al. modify the volume of music stereo playback to guide users toward their destination in the ONTRACK system [4]. The full sound is given in both ears within an angle of 90 degrees around the target. Between 90 and 180 degrees, the sound is shifted 45 degrees to the left or right, and it is completely shifted to the left or right ear for angles above 180 degrees. Their field trial also showed that visual distraction may interfere with audio guiding.

The AudioBubbles concept by McGookin et al. [5] is similar to AudioGPS, but does not require the use of headphones. The context is somewhat different in that is not specifically targeted to navigation, but to support tourists to be aware of and locate points of interest while wandering freely. The SoundCrumbs application described by Magnusson et al. in [6] enables the user to place virtual spheres of sound in a virtual georeferenced system and locating them again to support finding ones way back to a starting location, or to create virtual trails to share with others. It is possible to locate the next soundcrumb on the trail by pointing - when the magnetometer points in the direction of the next sound crumb, it will be played with adjusted volume, depending on whether the user points directly at the target or beside it.

Instead of using audio as a beacon at the target, tactile feedback such as vibration has also been used. In the SweepShake system presented by Robinson et al. [7] the user point in a direction and receives vibratory feedback when the device is pointing at the target. The targets are different in size depending on their information content (a larger target indicates more information content) and the use case described is primarily browsing and selecting geolocated information while standing still. Ahmaniemi & Lantz [8] similarly use vibratory feedback to investigate target finding speed in a laboratory set-up. The user scans or sweeps a handheld device while standing still. The study considered feedback angles between 5 and 25 degrees, concentrating on the speed of the sweeping movement. The possibility of missing the target at high speeds for smaller angles is stated. The results show that reaching a target with a vibratory angle of 5 degrees is significantly more difficult than with larger angles. The Social Gravity system described by Williamson et al. [9] intends to guide a group of people toward a common meeting point, called a “centroid” that adjusts its position according to the individual members of the group, using vibration feedback. The users are also here expected to scan for the target (centroid), and a 60 degree target indication angle was used in the field trial. Before choosing the field trial angle a simulations was made with angles from 5 to 180 degrees.

A more detailed study on the influence of angle size on performance, gestures and strategies in a more real outdoor navigational setting is still missing. The present study is aimed at improving this state of affairs.

2 Test description

The present study was set up to answer the following questions: What happens when you vary the angle interval? Is there a preferred angle? What kind of strategies/gestures do the users adopt when interacting with this type of pointing application?

For the test we used an external magnetometer (a SHAKE SK 6 device) connected via Bluetooth to a Sony Ericsson Xperia mobile phone running Windows Mobile. The test was done within a limited space outdoors. Most test rounds were done in a park like area outside our department which contained open areas, foot/bike paths, trees, bushes and some artistic installations. We had decided on this type of fairly open environment for several reasons:

- A road network would impose a limited number of possible directions making it harder to discern the effect of the angle interval alone.
- One can expect users to visit parks and open squares, and the test environment contained elements natural for that type of environment.
- This type of environment allows more freedom in the design of different trails.

To see what happens in a completely open environment we also carried out three tests in an open field further away. The test tracks at both locations were based on a grid structure (see Fig. 1 A).

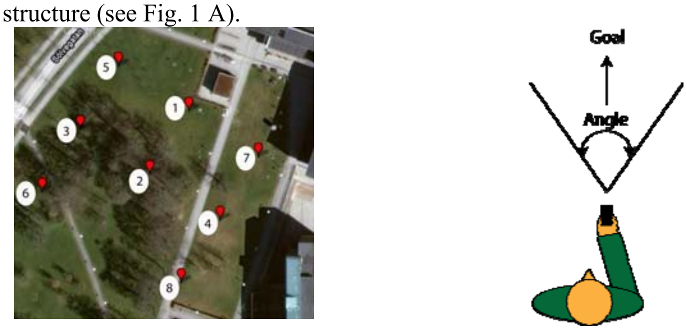


Fig. 1. A) The grid points for the test trails. B) The angle interval.

The four different tracks available can be worked out from Fig 1A. Each track started at point 1 and went on to point 2. At 2 you could turn either left or right. The same would happen at the points 3 or 4. The track ended at one of the corner points 5,6,7 or 8. The turns at the points 2, 3 and 4 were made in an alternating fashion so that if you turned left at the first turning point the first trial, you turned right during the next trial. Thus if your first trail was 1, 2, 3, 6 and your second trail 1, 2, 4, 8 your third trail would be 1, 2, 3, 5. The same design was used for the following turn. The initial values for the turns in the sequence were assigned randomly. Since there were four tracks and eight tests each track occurred twice. Due to both GPS inaccuracy as well as deviations due to different angle intervals the users did not walk the same way every time even though the underlying GPS track was the same. When asked about it after the test, none of the users had noticed that some paths were the same. Furthermore the order in which the angle intervals were presented was randomized to cancel out possible learning effects.

The grid distance in the (5,1,7) direction was 37 m while the distance in the perpendicular direction (1,2) was 33 m. Each point in the track was surrounded with a circle of an approximate[1] radius of 10 m. If the user was inside this radius the application would lead the user towards the next point in the sequence. When the user was within an approximate radius of 20 m of the goal waypoint the phone started to vibrate slowly. When the user was 10 m (or closer) to the target the goal was considered reached and the phone started to vibrate quickly.

The user got information about which direction to go by pointing the device in different directions (as was done in [6] and [9]). If the device was pointing in the right direction audio feedback playing a wave file (the sound of waves against the shore) was played. The volume did not change – the sound was either on or off. The direction was considered to be right as long as the device was pointed to a direction within a specified angle interval as shown in Fig 1B.

The angle intervals tested were 10º, 30º, 60º, 120º, 150º and 180º. The order in which these were presented to the test person was randomized. A practice round at 30º was carried out before each test.

The users were observed during the test. After the test they were asked about which strategies they used for small and large angles, how much they felt they needed to concentrate or if they had any other comments about the interaction design. The test application logged time, GPS position and magnetometer heading. It also logged when the user passed different waypoints and when the goal was reached.

15 persons did the test. Of these users, 6 were female and 9 male. The age range was wide – our youngest test user was 13 while the oldest person who did the test was 70.

3 Results

Contrary to our expectations users were not very sensitive to the angle interval. Even for the 180º condition all test users found the goal.

Some differences were still seen. If we start by looking at the time to find the goals in table 1 we see that on the whole the 10º angle interval and the 180º angle interval takes longer. Statistical analysis using ANOVA showed significant differences ($p<0.0001$). A Bonferroni test showed significant differences with a confidence level of 95% between 10º and the angle intervals 30º, 60º, 90º and 120º. 180º was significantly slower than all other intervals except 10º. That the 10º and 180º conditions take longer to complete can be seen clearly if we look at the average times. We also note that there is little difference between the 30º, 60º, 90º and 120º angle intervals.

If we instead look at the trails we can pick up some general features. As expected the more narrow angles lead to more precise route following, while for the wider angles people would stray more and would even occasionally walk in circles for a while.

[1] The formula used in the implementation overestimated longitudinal distances with a factor of 1.19 compared to the haversine formula. For distances of 10 m this is within the GPS accuracy and should not influence the outcome of the test.

Table 1. Time in minutes to find the goal for different angles.

Nr	10º	30º	60º	90º	120º	150º	180º
1	5,32	4,31	3,93	3,49	3,52	5,65	4,49
2	2,89	2,65	2,62	3,71	1,75	3,12	2,52
3	4,27	3,16	3,24	2,89	2,91	2,35	5,81
4	5,02	2,85	2,82	2,43	3,66	3,56	8,25
5	6,48	2,16	2,27	2,01	2,13	2,61	2,52
6	4,09	3,26	2,33	2,37	2,00	2,73	7,22
7	2,50	2,95	2,19	1,77	2,28	6,02	8,89
8	6,87	3,43	2,51	2,90	2,08	2,68	6,26
9	3,23	2,01	1,94	1,82	1,93	1,53	2,34
10	2,78	2,29	2,09	3,13	2,58	5,72	5,29
11	3,19	1,78	2,26	2,96	1,85	2,14	5,13
12	5,14	3,21	3,21	2,43	4,58	2,88	5,59
13	6,23	3,05	2,50	2,87	2,88	4,42	4,69
14	7,50	3,65	2,60	2,92	2,58	3,67	3,35
15	5,41	2,66	2,69	2,09	3,71	2,79	10,09
Av	4,73	2,89	2,61	2,65	2,69	3,46	5,50

Looking at the three tests done on an open field we can see the trend quite clearly. In the top row of Fig. 2 we see the angles 10º, 30º, 60º and 90º. All these trails follow the intended path quite well, although we begin to see some deviations in the rightmost picture. In the bottom row of Fig. 2 we see the wider angles resulting in more deviations and finally also loops.

Fig. 2. Trails for 10º, 30º, 60º, 90º (top row), 120º, 150º and 180º (bottom row).

At the main (more realistic) test location there were objects such as trees, footpaths, cyclists etc that the test persons would have to avoid. In addition we also had more problems with the GPS signal. The trend is still the same, as can be seen from Fig 3. In the top row of Fig 3 we can see the intended paths quite clearly. In the bottom row things are getting less and less organized and the last picture at the bottom right shows a spaghetti like mess where several trails appear to make loops as well as deviating a lot from the intended paths. All these pictures were made with GPSVisualizer, http://www.gpsvisualizer.com/.

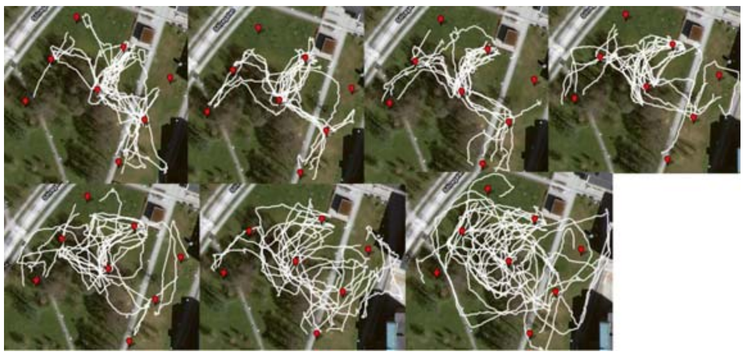


Fig. 3. Trails for 10º, 30º, 60º, 90º (top row), 120º, 150º and 180º (bottom row).

For the finding of the appropriate direction while standing still we saw three main types of gestures. The first, which basically all users made use of, was to hold the device out in front of the body, keeping the arm and hand position fixed relative to the body, and walk around on the spot (sometimes in a small circle). A second gesture which was used both while walking and while standing still was the arm scan. In this gesture the arm was moved to the side and back again. This gesture occurred to one side only or from side to side. The third type of gesture was hand movement only – the user moved the hand by flexing the wrist. Also this gesture was used both standing still and while walking. In addition two users also scanned by keeping the hand and arm still, but instead walking in a zig-zag/serpentine fashion forwards. One user also tried to scan by moving the device with the fingers (keeping the hand in the same position).

For finding the direction while standing still all the three main gestures were used. Some users preferred the whole body rotation only, while some started with the arm pointing and only made use of whole body rotation if this didn't give any result. The hand pointing was mostly used for the narrow angles (10º and sometimes also 30º).

In general our users would keep walking as long as they heard the audio feedback. When they lost it they stopped and checked the direction. The only exception was the 10º angle. As was noted already in [8] narrow angles make targets easy to miss, and for this angle it was really hard to keep a steady signal. This led either to the person stopping a lot, or to keep walking a while without signal and then stopping to check if he or she was walking the right way. Some users also tried to use arm or hand scan while walking to keep the signal, but given the noise in the signal, the limited update rate and the delays present this tended to work badly leading instead to a complete loss of signal.

For the wider angles we saw that we had two basic types of users. One group was more analytic and explored the width of the angle interval and then tried to walk towards the middle. The other group walked as soon as they felt they had a steady signal. The difference between the groups was most clearly seen in the 180º condition; although some of the more analytical users also had problems with this angle interval in general the analytical strategy made users better able to cope with the wider angles. In the analytical group we would often see the user trying to check the limits of the angle interval by doing a sideways scan (while walking) to find the border. The less analytic users would still tend to avoid the borders of the angle interval. Due to noise/jumps in the magnetometer signal the sound would start "hiccupping" near the border. All users made use of this info, although not everyone realized this was useful right from the start. While scanning standing still, this meant that the user would keep moving the device until the signal was steady (and often a little further) which meant that also the less analytic users would avoid walking right along the borders of the angle interval. While walking, the hiccup would either trigger a stop to scan a new direction, or the user would try to re-orient by doing an arm scan while walking.

In general users expressed that they felt more "secure" with the wider angles (although they didn't like the 180º which was said to be too wide). The 10º made users feel insecure, and they walked noticeable slower in this condition. We did not explicitly test cognitive load, but we did probe this by trying to talk to our subjects. Both from the responses to this, and also from answers to explicit questions it was clear that the narrow angles were more demanding. Particularly the 10º angle required a lot of concentration from the user. One user said "you have to concentrate so hard that you almost forget where you are". All users disliked the 10º and thought it was too narrow. With wider angles people were more relaxed and would often start talking spontaneously with the observer. They also commented that with larger angles you didn't have to concentrate that much, but could relax and enjoy the walk.

4 Discussion

Contrary to our expectations our test users were surprisingly insensitive to the size of the angle interval. Our results indicate that also wider angles such as 90º and to some extent even 120º can work reasonably well. Our test results confirm that we had included a sufficient range of angle intervals – we had both a too narrow angle (10º) and a too wide one (180º). In between those the recommendation for which angle to use depends on several factors:

- If it is important to get exact track following one should go for more narrow angles. This depends to some extent on the equipment at hand but from this test we would recommend 30º to 60º.
- If you want a design that puts small cognitive load on the user it is better to use wider angles. Judging from the results of this test 60º to 120º works for this purpose.
- In general people walk slower if the angle is too narrow. If you are targeting applications where the user wants to walk quickly or maybe even run (eg. jogging applications) wider angles are preferable.

The 60º used in [9] agrees with these findings. Even so, the task dependence of the recommendations indicates that angle interval is a variable which should be possible to customize.

The fact that the 10º angle is difficult is very much depending on uncertainties in the signal (a nice overview of this topic can be found in [10]) combined with a discrete sampling rate. When the heading value "jumps" due to noise it is easy to miss the goal completely. The risk of missing the target if it is narrow is also pointed out in [8]. Thus, one factor which influences these recommendations is the properties of the hardware. With faster and more precise equipment one can expect that smaller angles will be easier to deal with. The general trend that smaller angles favor more precise but also more cognitive demanding navigation can still be expected to hold.

We were a bit surprised that all users found the goal also in the 180º condition. Although they would sometimes walk in wrong directions and also on occasion walk in circles they would eventually converge on the target. Potentially this could be due to obstacles in the environment causing fortunate deviations, which is why we did a few tests also in a completely open environment – and also in the open environment users were able to get to the goal eventually.

The size if the track points was set to a size that initial tests showed resulted in smooth navigation. With smaller track point size we would expect a need for more exact navigation. It should be noted that the actual directions used for the angle feedback was calculated using the GPS point in the middle of the circle so the size of the circles would not have any effects on the direction information provided to the user - it influences only which track point the application thinks the user is looking for and when the user is considered to have reached the goal.

It should be noted that our results are for a fairly open environment. In a street grid environment the number of possible directions is limited, and wider angles can probably be used without loss of precision (as an example: if you are walking along a road even a 180º interval is likely to tell you if you are heading in the correct direction or not).

Another outcome of our study is an improved understanding of the strategies users employ. Some users are more analytical and will scan the extent of the interval and try to walk towards the center, while others will "just walk" when they get a signal. In general users find it quite natural to scan, which implies that it is important to make use of a compass that is fast enough to support this behavior. The device used for these tests (the SHAKE SK6) was fast enough to support scanning although very fast gestures had to be avoided. It also had a filtering mode that gave more steady headings – but pilot tests showed that this unfortunately slowed down the compass too much when used with the scanning gestures.

The pointing interaction used in this study appeared to be easily understood, and none of our users had any noticeable problems dealing with it. This is in agreement with the results in [7] and [9] who also find this type of pointing/scanning interaction easy and intuitive for users.

The audio used (a sound of waves against a shore) was well liked. It was quite easy to hear, but even more importantly it wasn't perceived as annoying or disturbing. Even the person who observed the tests and who listened to it for more than 17 hours found it nice to listen to. One further advantage of using a continuous sound was the "hiccupping" that happened near the borders of the angle interval which provided extra information. In a sense the continuous nature of the sound source made it easier to discern changes in signal. This agrees with the observation in [11] that changes in data are better mapped using continuous feedback – in this case audio. In the case of Geiger counter type designs (such as was used in [1]) you will miss this information. In cases where you want to mask irregularities in the signal this could be used to your advantage, but in the present case the border information is quite valuable.

In this study we used only sound on or off as feedback since adding different sectors in the angle interval would introduce more factors that might influence the results and we wanted to focus on the basic influence the width of the interval. This does not mean that it is not a good idea to vary the feedback to give the user the advantage of having both a more precise direction combined with the advantages a wider angle provides. One example of such a design can be found in [6] where a central interval of 30º with 100% volume was followed by an interval out to 90º where the volume was 40%. Outside this the sound played at 20% level all the way up to 180º.

5 Conclusion

The present study was performed in order to get a better understanding of the influence of angle size on navigation performance, gestures and strategies in a more realistic outdoor setting. We have been looking at what happens when you vary the angle interval, if there is a preferred angle, and what kind of strategies/gestures the users adopt when interacting with this type of pointing application.

We find that users are able to handle quite a wide range of angle intervals. The only intervals generating significantly slower completion times were the 10º and 180º angle intervals. Among the angle intervals that appear to be working reasonably well, we still find some differences. Narrow intervals provide more exact track following but may be slower and require more attention/concentration from the user. Wide angle intervals result in less exact track following, but allow users to walk faster and be more relaxed. Thus there is no single preferred angle interval – instead this depends on the task. If exact track following is important we would recommend an interval of 30º to 60º while we recommend an interval of 60º to 120º if low cognitive load is important. The 60º used in [9] agrees with these findings. The task dependence of our recommendations indicates that angle interval is a variable which should be possible to customize. It should be noted that the precise angle intervals in these recommendations depend both on hardware properties as well as the size of the circle around each track point within which the point is considered to be reached. The general trend indicated above should still be expected to hold.

In this test we observed three main scan gestures: the whole body scan, arm pointing and hand pointing. Users tended to keep walking as long as they had a signal and stop to scan for direction if they lost it. Some users scanned also while walking. For narrow angles this was done in order to keep the signal, while if it was performed for wide angles the scanning would be to check that the user was still heading roughly towards the middle of the angle interval. We have seen two basic types of strategies for dealing with the interaction: we have the analytic strategy where one checks the size of the interval and then tries to head for the center, and we have the direct strategy where you scan until you get a signal and then head in that direction.

Finally, our observations extend the observation made in [7] that this type of pointing gesture is intuitive and easy to use also for navigational purposes.

Acknowledgments. We thank the EC which co-funds the IP HaptiMap (FP7-ICT-224675). We also thank VINNOVA for additional support. The authors also gratefully acknowledge discussions with David McGookin and Stephen Brewster from the Multimodal Interaction Group in Glasgow.

6 References

1. Holland, S., Morse, D.R., Gedenryd, H. (2002): "Audiogps: Spatial audio in a minimal attention interface". Personal and Ubiquitous Computing 6(4)
2. Strachan, S., Eslambolchilar, P., Murray-Smith, R., Hughes, S. and O'Modhrain S. (2005): "GpsTunes: controlling navigation via audio feedback" In Proceedings of the 7th international conference on human computer interaction with mobile devices & services (MobileHCI '05)
3. Stahl, C. (2007): The roaring navigator: A group guide for the zoo with shared auditory landmark display. In Proceedings of the 9th international conference on Human computer interaction with mobile devices and services (MobileHCI '07)
4. Jones, M., Jones S., Bradley, G., Warren, N., Bainbridge, D., Holmes, G., (2008): "ONTRACK: Dynamically adapting music playback to support navigation" Personal and Ubiquitous Computing 12(5)
5. McGookin, D., Brewster, S., Prieg, P., (2009): "Audio Bubbles: Employing Non-speech Audio to Support Tourist Wayfinding", In Proceedings of the 4th international workshop on Haptic and Audio Interaction Design (HAID '09)
6. Magnusson, C., Breidegard, B., Rassmus-Gröhn, K.: (2009) "Soundcrumbs – Hansel and Gretel in the 21st century", In Proceedings of the 4th international workshop on Haptic and Audio Interaction Design (HAID '09)
7. Robinson, S., Eslambolchilar, P., Jones, M. (2009) "Sweep-Shake: Finding Digital Resources in Physical Environments", In Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '09)
8. Ahmaniemi, T., Lantz, V., (2009): "Augmented Reality Target Finding Based on Tactile Cues", In Proceedings of the 2009 international conference on Multimodal interfaces (ICMI-MLMI'09)
9. Williamson, J., Robinson, S., Stewart, C., Murray-Smith, R., Jones, M., Brewster, S. (2010) : "Social Gravity: A Virtual Elastic Tether for Casual, Privacy-Preserving Pedestrian Rendezvous" Accepted for publication in Proceedings of the 2010 Conference on Human Factors in Computing Systems (CHI 2010) (Private communication)
10. Strachan, S. and Murray-Smith, R. 2009. Bearing-based selection in mobile spatial interaction. Personal Ubiquitous Comput. 13, 4 (May. 2009), 265-280.
11. Sawhney, N. and Murphy, A. 1996. ESPACE 2: an experimental hyperaudio environment. In Conference Companion on Human Factors in Computing Systems: Common Ground (Vancouver, British Columbia, Canada, April 13 - 18, 1996).

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.

R. Nordahl et al. (Eds.): HAID 2010, LNCS 6306, pp. 117–128, 2010.

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.

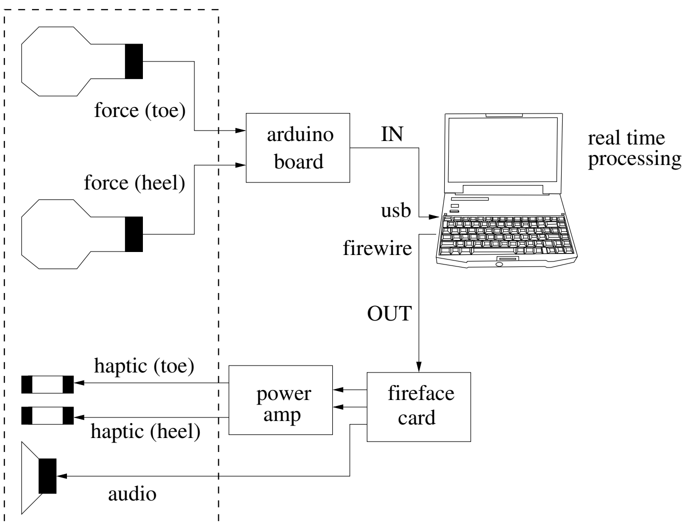


Fig. 2. Illustration of the prototype components. Sensors and actuators of one shoe are surrounded by the rectangle in dashed line.

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.

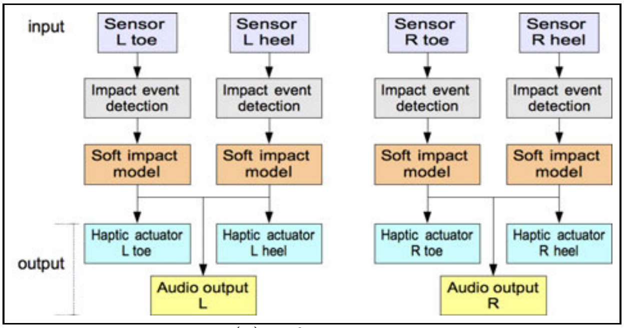
The *soft impact* model has been used to simulate the contact between a shoe and homogeneous floors or wet grounds, in particular providing two separate envelopes corresponding respectively to the heel and the toe. The aim was to add resonances to neutral floors in order to change the perceived ground 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.

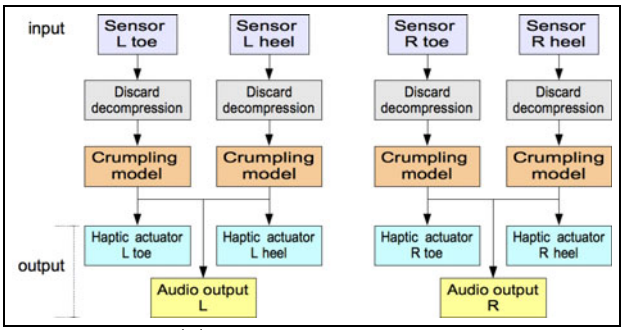
Both the temporal distribution of crumpling events and their own power follow stochastic laws which are derived from physics [14]. Such laws govern 1) the energy dissipation occurring during an impact, and 2) the temporal distribution of adjacent events. Each phenomenon exposes a characteristic parameter,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



(a) soft impact



(b) continuous crumpling

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

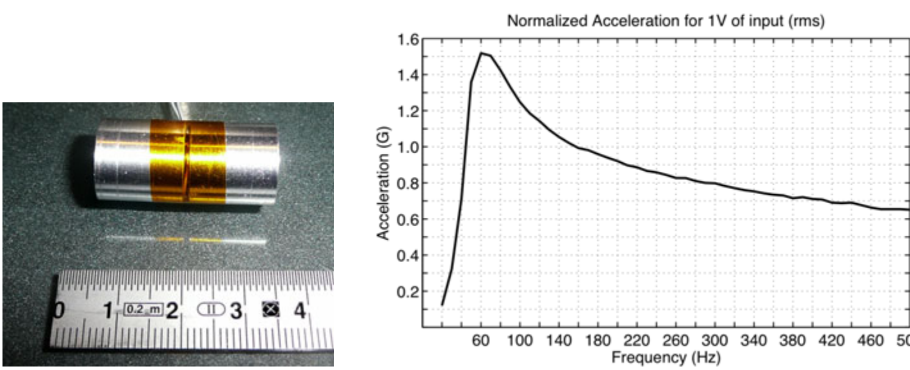
The high-rate data stream coming from the Arduino accounts for the force signals measured at each foot's toe and heel. These four signals are received by a Pd patch communicating with the Arduino, and then routed to the SDT model in use. Moreover, the same patch can save the force signals as text files (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.

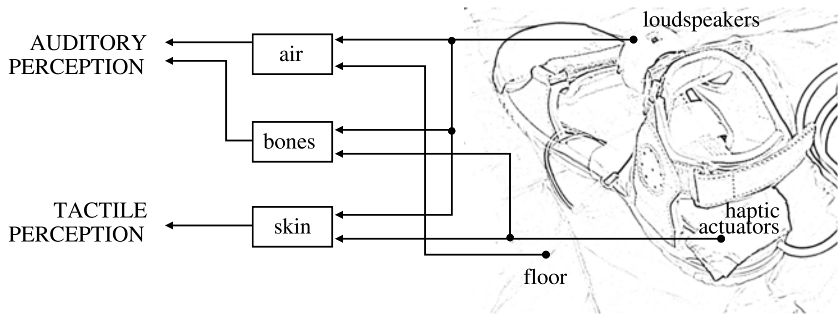


Fig. 5. Information paths connecting the actuated shoes to the auditory and tactile perception

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.

Acknowledgments

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

References

1. Iwata, H.: Haptic interface. In: Sears, A., Jacko, J.A. (eds.) The Human-Computer Interaction Handbook, 2nd edn. Lawrence Erlbaum Assoc., New York (2008)
2. Visell, Y., Fontana, F., Giordano, B., Nordahl, R., Serafin, S., Bresin, R.: Sound design and perception in walking interactions. Int. J. Human-Computer Studies, 947–959 (2009)
3. Giordano, B.L., McAdams, S., Visell, Y., Cooperstock, J.R., Yao, H., Hayward, V.: Non-visual identification of walking grounds. In: Proc. of Acoustics 2008 in J. Acoust. Soc. Am., vol. 123(5), p. 3412 (2008)
4. Norman, D.: The Design of Future Things. Basic Books, New York (2007)

5. Visell, Y., Cooperstock, J.: Design of a vibrotactile device via a rigid surface. In: Proc. of the IEEE Haptics Symposium, Waltham, MA (2010)
6. Papetti, S., Fontana, F., Civolani, M.: A shoe-based interface for ecological ground augmentation. In: Proc. 4th Int. Haptic and Auditory Interaction Design Workshop, Dresden, Germany, vol. 2 (2009)
7. Civolani, M., Fontana, F., Papetti, S.: Efficient acquisition of force data in interactive shoe designs. In: Proc. 5th Int. Haptic and Auditory Interaction Design Workshop (2010); Elsewhere in these proceedings
8. Bresin, R., de Witt, A., Papetti, S., Civolani, M., Fontana, F.: Expressive sonification of footstep sounds. In: Bresin, R., Hermann, T., Hunt, A. (eds.) Proc. of the Interaction Sonification workshop (ISon) 2010, KTH, Stockholm, Sweden (2010)
9. Rocchesso, D., Fontana, F. (eds.): The Sounding Object. Mondo Estremo (2003), http://www.soundobject.org/
10. Papetti, S.: Sound modeling issues in interactive sonification: from basic contact events to synthesis and manipulation tools. PhD thesis, University of Verona, Italy (2010)
11. Adrien, J.M.: The missing link: Modal synthesis, pp. 269–297 (1991)
12. Fontana, F., Bresin, R.: Physics-based sound synthesis and control: crushing, walking and running by crumpling sounds. In: Proc. Colloquium on Musical Informatics, Florence, Italy, pp. 109–114 (2003)
13. Bresin, R., Delle Monache, S., Fontana, F., Papetti, S., Polotti, P., Visell, Y.: Auditory feedback from continuous control of crumpling sound synthesis. In: CHI 2008 Workshop on Sonic Interaction Design, Florence, Italy. ACM, New York (2008)
14. Houle, P.A., Sethna, J.P.: Acoustic emission from crumpling paper. Physical Review E 54, 278–283 (1996)
15. Visell, Y., Cooperstock, J., Giordano, B.L., Franinovic, K., Law, A., McAdams, S., Jathal, K., Fontana, F.: A vibrotactile device for display of virtual ground materials in walking. In: Ferre, M. (ed.) EuroHaptics 2008. LNCS, vol. 5024, pp. 420–426. Springer, Heidelberg (2008)
16. Hayward, V., Dietz, G., Berrezag, A., Visell, N.O.Y., Cooperstock, J.: Haptic device engineering for walking interactions. Deliverable 2.1, NIW project (2009), http://www.niwproject.eu
17. Altinsoy, E.: Auditory-Tactile interaction in Virtual Environments. Shaker Verlag, Aachen (2006), http://www.ias.et.tu-dresden.de/akustik/Mitarbeiter/Altinsoy/data/15.pdf

Efficient Acquisition of Force Data in Interactive Shoe Designs

Marco Civolani[1], Federico Fontana[2], and Stefano Papetti[1]

[1] Università di Verona, Department of Computer Science
strada Le Grazie, 15 – 37134 Verona, Italy
{marco.civolani,stefano.papetti}@univr.it
[2] Università di Udine, Department of Mathematics and Computer Science
via delle Scienze, 206 – 33100 Udine, Italy
federico.fontana@uniud.it

Abstract. A four-channel sensing system is proposed for the capture of force data from the feet during walking tasks. Developed for an instrumented shoe design prototype, the system solves general issues of latency of the response, accuracy of the data, and robustness of the transmission of digital signals to the host computer. Such issues are often left partially unanswered by solutions for which compactness, accessibility and cost are taken into primary consideration. By adopting widely used force sensing (Interlink) and analog-to-digital conversion and pre-processing (Arduino) components, the proposed system is expected to raise interest among interaction designers of interfaces, in which the reliable and sufficiently broadband acquisition of force signals is desired.

Keywords: Force sensing, closed-loop interfaces.

1 Introduction

Assessment of human gait has been a well known issue in biomechanics and biomedical engineering. Early experiments in measuring and evaluating forces under the foot date back to the end of the 19th century (Beely, 1882; Momburg, 1908). Since that time, various techniques and methods have been implemented with the same purpose, involving the use of different kinds of floor-based electromechanic transducers [1,2,3].

Within this specific research topic, we are currently developing an instrumented shoe design that virtually reproduces ground surfaces, by interactively augmenting otherwise neutral (i.e., flat and homogeneous) floors [16]. By means of appropriate force sensing, real time signal processing, and final displaying of multimodal (audio and tactile) cues through portable loudspeakers and haptic actuators underfoot, this design is expected to serve purposes such as navigation in functional spaces, support to physical rehabilitation, and entertainment.

While planning the design of a sensing system for such shoes, we wanted to reach an acceptable trade off between accuracy of the recorded data and accessibility and cost of the technology. Furthermore, the same system had to deliver a

R. Nordahl et al. (Eds.): HAID 2010, LNCS 6306, pp. 129–138, 2010.

continuous data flow affording tight close-loop interaction with walkers through the real time processing of such data. Recently, small and light force sensing devices have been developed, allowing for within the shoe, online force measurements. In parallel, the exploitation of powerful integrated electronic devices has led to the design of portable and wearable data acquisition systems [4,5,6,7].

Unfortunately, there is a general lack of simple yet reliable wearable force measurement systems. It is true that biomechanical and biomedical researchers and engineers can choose commercial solutions providing integrated hardware and software platforms for accurate underfoot force measurements and gait analysis (see for example the Tekscan product line). Besides their quality, hardly these solutions can be adapted for prototyping novel, flexible concepts of foot-floor interfaces. Furthermore, integrated technologies like these do not always guarantee low-level accessibility to raw data, nor they specify exact figures of latency for the transmission of the related signals.

For these reasons, we have worked on the in-depth optimization of an architecture based on popular hardware in the interaction design field, made by Interlink[1] and Arduino[2] and overall costing few tens of dollars. Its performance depends on the number and characteristics of the sensors and the specifications of the acquisition board: together, they set the dynamic range and the band of the acquired information. Besides its applicability to instrumented shoes, the same architecture is of potential interest in all situations where accurate force data must be acquired and processed in real time.

This paper describes in detail its design and operation inside our prototype.

2 Sensors

Two Force Sensing Resistors (FSR) have been inserted between a sandal and a removable sole, forming an additional layer on top of the sandal itself (Fig. 1). Interlink equipment was chosen, for its versatility and popularity among interaction designers [8]. In this sort of "sandwich" configuration, the two sensors detect forces respectively in correspondence of the toe and the heel.

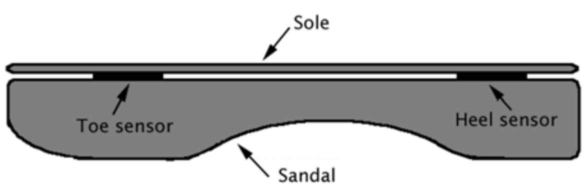


Fig. 1. Mechanical assembly of the shoe. For both toe and heel the Interlink FSR model 402 has been used.

[1] `http://www.interlinkelectronics.com/`
[2] `http://arduino.cc/`

Each FSR is connected in series with a fixed resistor. Together, they realize a voltage divider. The four dividers, two for each shoe, are finally connected to the first four analog inputs of an Arduino Duemilanove board, another quite popular device. Fig. 2 illustrates this connection.

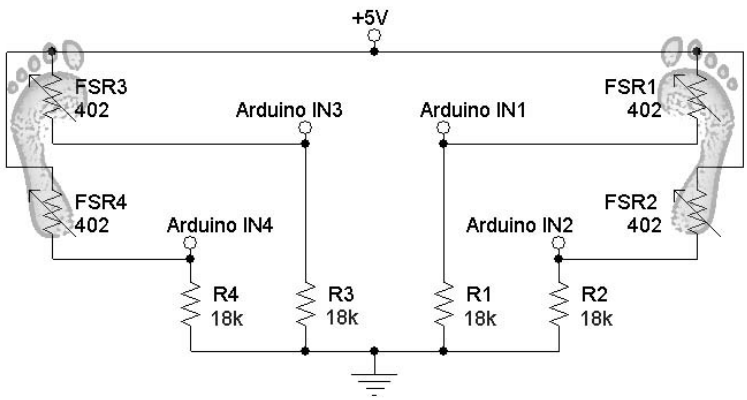


Fig. 2. Schematic of the conditioning circuit. The 5 V and ground pin are accessible from the Arduino board.

A previous version of the prototype used different sensor models and resistance values in the voltage divider [9]. In the following we will see that optimizing these two components leads to substantial improvements.

2.1 Characterization of the FSR

Interaction designers know that Interlink force sensors have good response in front of rapid and large changes in the applied force [10], and they are also especially robust [11]. Thus, they are suitable for detecting forces such as those typically exerted by the foot during gait. For their small size, the model 400 and model 402 are the only Interlink products that can find place inside a shoe without risk of breaking due to excessive mechanical deformation. Although quite similar, the model 400 overall exhibits a different behavior compared to the 402 [12]: in our previous prototype, a good balance between front and rear sensitivity had been achieved by placing a model 400 under the heel and a 402 under the toe.

While changing shoe model during the development of the current prototype, we found that the model 400 reaches mechanical saturation much faster than the 402. This overall unbalanced the acquisition of the data. Clearly, the foot pressure had a different distribution in the new sole.

Measurements have then been made to characterize their behavior. The same measurements furthermore proved useful to characterize the nonlinear behavior of the overall system, caused by the electrical coupling between the FSR and the

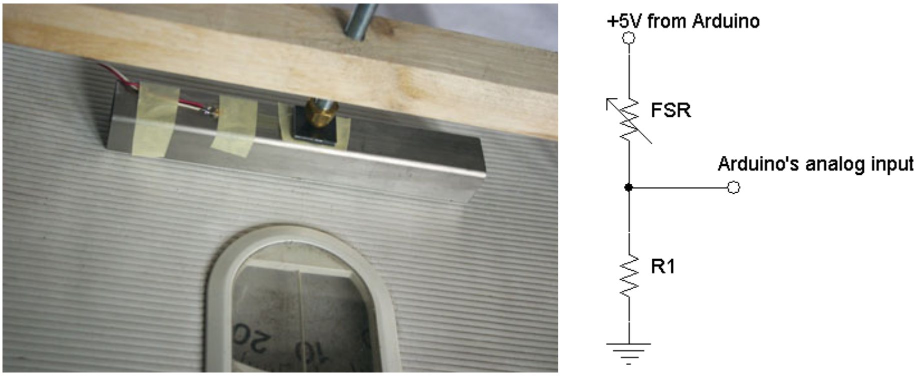


Fig. 3. Characterization of the FSR. (left) Mechanical setup. (right) Voltage divider for the acquisition of measured forces.

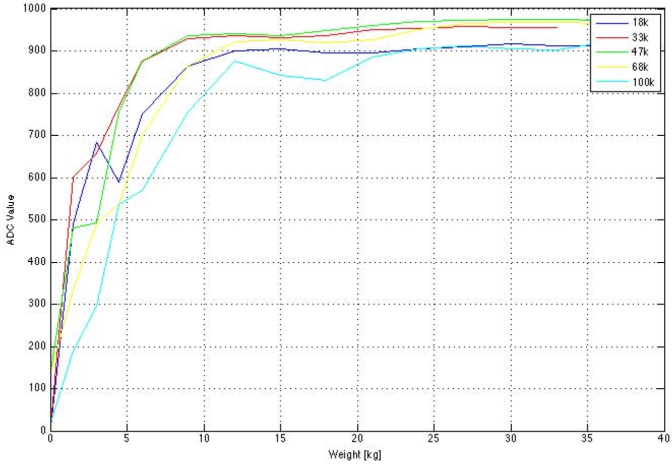
analog-to-digital converter (ADC) in the Atmel microcontroller on-board the Arduino [13].

A manual wooden press has been built, and mounted onto a weighing scale. This press had an interchangeable termination, providing mechanical matching with the active area of the sensor. With this simple setup, we could read the value of the force exerted by the press over the sensor. Fig. 3 (left) shows the setup.

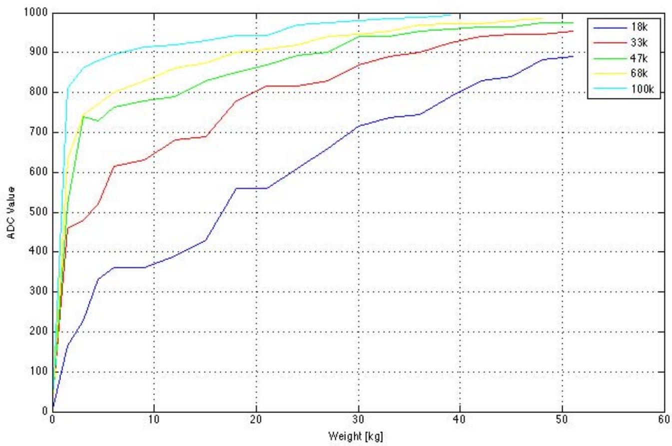
The voltage divider containing the FSR was connected to the Arduino analog input as shown in Fig. 3 (right), then pressed. As a result of this simple test, several sets of curves have been obtained for each sensor mapping force into ADC values, for changing values of the resistance R1 in the voltage divider. In practice, each curve represents the relationship between the applied force and the ADC output (ranging from 0 to 1023) for a specific value of R1. Fig. 4 displays the corresponding plots, respectively for sensors model 400 (a) and 402 (b). Their inspection shows that the system is more linear when using the model 402.

All measurements were made by choosing standard resistance values for R1 below 100 kΩ. Smaller values result in a smoother response that furthermore reduces the dynamic range, particularly with the model 402. This means that when the FSR reaches mechanical saturation, the voltage across R1 is below the maximum input voltage of the ADC (5 V). Conversely, values amounting to more than 100 kΩ introduce a strong nonlinearity. Choosing R1 = 18 kΩ results in a good compromise between range and linearity of the system.

In conclusion, the model 402 has been preferred for all sensing points and the resistance in the voltage dividers has been set to 18 kΩ: these choices have substantially improved the sensitivity of our instrumented shoes. Besides our specific application case, a simple measurement experience like the one described here can reward each time an FSR must be coupled to an ADC in an acquisition system of interest.



(a) Model 400.



(b) Model 402.

Fig. 4. Force/ADC maps for changing values of R1

3 Firmware

A good firmware program can enable the cheap hardware on-board the Arduino to perform as an effective front-end for data acquisition from the sensors. A reliable analog-to-digital conversion along with a low-latency transmission of the acquired data are in fact necessary to achieve this goal, when designing a real time interactive system providing instantaneous feedback. The essential tasks of the Arduino are illustrated in Fig. 5.

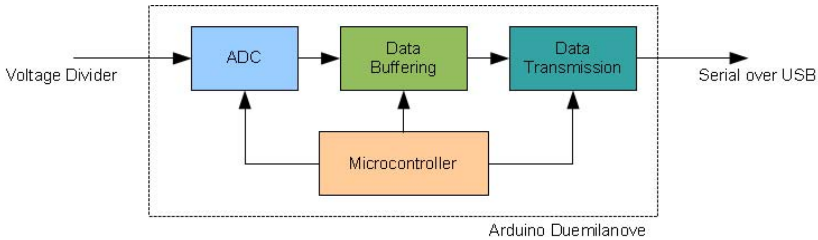


Fig. 5. Blocks of the data acquisition module

The firmware employed in the previous prototype of the interactive shoes included an application program, that repeatedly read the four values coming from the respective analog inputs through a traditional polling procedure nested inside a main loop [9]. Then, data were filtered in such a way that a packet containing the values was sent only if two subsequent samples differed at least by a given threshold. Concerning the serial transmission, we sent to the host packets made of four ADC values separated by a space character. Each packet ended with a separator (end of line) character.

Both the polling sequence and the transmission routine have been written using functions and procedure calls provided by the Arduino SDK. The use of this framework allows to write code very easily, thanks to the good level of abstraction provided by the embedded C++ API. Unfortunately the compiled program is often not efficient enough, especially if running on applications requiring a constantly low latency during the acquisition of uniform data flows.

In our case, the unconditioned use of the API affected the reliability of the analog-to-digital conversion and the constancy of the transmission rate of the serial connection over USB from the Arduino to the host. In fact, the previous firmware used the `analogRead` function, which, as a normal practice in acquisition procedures of this kind, was called for every channel during polling. As a consequence, the sampling frequency could not be kept stable: the main loop in fact can be interrupted at any moment, and it takes an unpredictable time for the system to return to the application program.

The transmission was managed using the `Serial.print` function, which prints out data to the serial port in the form of ASCII characters. In particular, every number digit was printed using the respective character. Once again, the API-based solution is quite standard and easy to be coded, but poorly performing. For instance, transmitting four 10-bit values requires, in the worst case (i.e., all the four values greater than 1000), $8 \cdot 4 \cdot 4 + 8 \cdot 4 = 160$ bits.

Interrupts can introduce heavy jitter. In the Arduino this problem is a consequence of the weak control of the low level structures inside the microcontroller through the API. In essence, the Arduino is not provided with resources capable to handle both processes in parallel:

- the ATMega168 is a single-thread machine, thus when the CPU is handling the ADC interrupt it cannot (among other things) transmit data over the serial connection;
- the Arduino USB connection is controlled by a FTDI FT232RL chip, which *emulates* a serial RS-232 connection over a USB line.

A consequence of the first point is that sampling with an exceedingly high frequency is unsafe since some values would be inevitably lost. The second point deals with the buffers that are present on the transmitter (inside the FTDI chip) and the receiver (in the USB controller driver, run by the operating system of the host computer). These buffers are governed by independent schedulers and procedures [14], and a low-level debugging of their mutual activity is a hard task.

As it often happens in this kind of architectures, the best performance is achieved by writing part of the code in assembly language at the cost of decreased readability and portability. A solution in between, that can be adopted with AVR-compliant microcontrollers like the ATMega168, is to write programs encoding API calls and AVR Libc instructions[3] together.

In the current firmware, we have set the ADC to work in *free-running* mode. Under this mode, the ADC interrupts the program only when the acquisition on the selected channel is completed. The sampling frequency can be selected by setting the ADC *prescaler* bits (ADPS) in the ADCSRA register. In free-running mode, a single conversion takes 13.5 CPU cycles, thus the sampling frequency turns out to be equal to $Fs = (16/13.5)/P$ MHz, where P represents the value of the prescaler.

Furthermore, a custom transmission protocol has been implemented [15]: binary data are transmitted instead of ASCII values using the `Serial.write` function. Every packet is formed by two bytes, B_{MSB} and B_{LSB}, such that their juxtaposition is $B_{MSB}\,B_{LSB}$ = 1CCCCVVV 0VVVVVVV. In this structure, the four bits denoted with C encode the channel number (16 channels are allowed), whereas the ten bits denoted with V encode the measured value thus guaranteeing sufficient accuracy for the acquired force. In the end, each sensor is assigned to a different channel. Hence, sending four values (one for each channel) using this protocol occupies a constant packet size, equal to $8 \cdot 2 \cdot 4 = 64$ bits.

3.1 Uniform Sampling of Force Data

We opted for a reliable, although not necessarily optimal assignment of the system variables in the new firmware, by empirically determining the transmission rates of in absence of drop-outs.

An oscilloscope was connected to a digital pin of the board. The pin was set at the beginning of the ADC routine, and was reset at the end of the same routine. The ADC routine called the transmission procedure only when the transmission buffer was full.

[3] `http://www.nongnu.org/avr-libc/`

When sending a cluster of bytes (i.e., a buffer) with the `Serial.write` function, the Atmel performs a serial transmission of data to the FTDI chip's buffer. For what we said above, data are sent on the USB line according to specific handshaking and buffering policies that in principle vary with the transmitter/receiver protocol.

The observations made on the oscilloscope uncovered that the serial transmission from the Atmel to the FTDI chip requires a large amount of CPU time. The values coming from the ADC which fall into this bottleneck are lost. For this reason we set the prescaler to $P = 128$, even if lower values are allowed.

By setting the buffer size to 2 bytes we obtained a regular sequence of impulses from the probed pin, testifying uniform sampling. In practice, this buffer size ensured that the transmission time is shorter than the sampling time. At this point, a linear relationship between the transmission rate and sampling frequency can be figured out. Table 1 lists possible choices complying with this relationship.

The values showed in Table 1 must be divided by the number of input channels, if a polling procedure is implemented. In our application, involving four channels, the sampling frequency per channel is $F_s = 5882/4 \approx 1470$ Hz. Considering that the FSR's have a response time of about 2 ms [12], a latency that is certainly smaller than any human response to psychophysical cue changes, the obtained sampling frequency is well above twice as much the Nyquist limit of $1/0.002 = 500$ Hz.

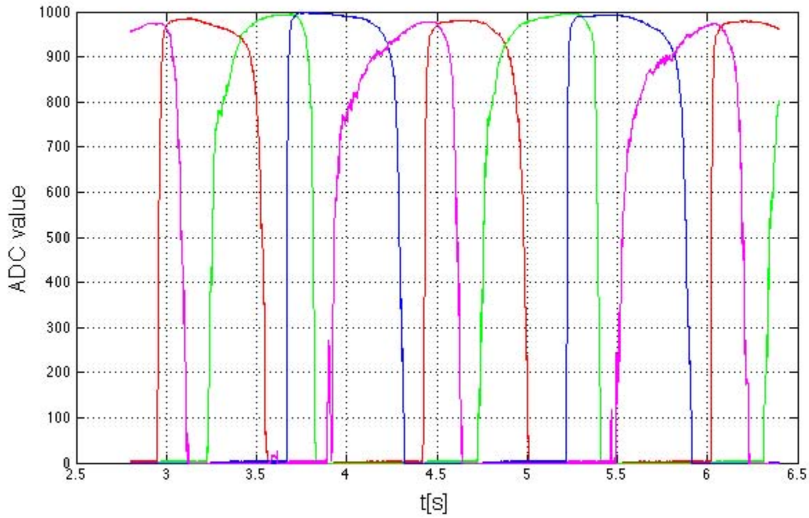
Table 1. Relationship between sampling frequency (F_s) and transmission rate (TXrate). Values per single channel. Prescaler set to 128.

TXrate [baud]	9600	19200	38400	57600	115200
T_s [ms]	2.1	1.04	0.52	0.36	0.17
F_s [Hz]	476	961	1923	2778	5882

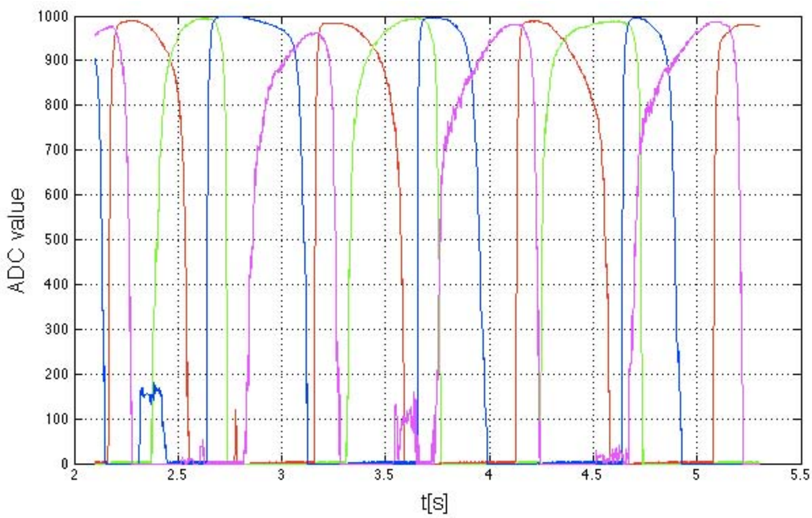
4 Results and Conclusions

Fig. 6 shows some plots of force signals recorded using the proposed system. These plots provide evidence of a substantial absence of noise and jitter in the data. If perhaps not accurate enough for applications where extremely high resolution is mandatory, such data is suitable for most interaction design and other applications.

In our case the force signals are sent to the host computer for further processing [16]. Still, for many other acquisition processes requiring similar performance and cost, we think that designers and others can make profitable use of the solutions and tests described in this work.



(a) Slow walk.



(b) Fast walk.

Fig. 6. Force plots. Red = left heel, green = left toe, blue = right heel, magenta = right toe.

Acknowledgments

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

References

1. Stott, J.R.R., Hutton, W.C., Stokes, I.A.F.: Forces Under the Foot. Journal of Bone and Joint Surgery 55-B, 335–345 (1973)
2. Manley, M.T., Solomon, E.: The Clinical Assessment of the Normal and Abnormal Foot During Locomotion. Journal of Prosthetics and Orthotics 3, 10–110 (1979)
3. Soames, R.W., Blake, C.D., Stott, J.R.R., Goodbody, A., Brewerton, D.A.: Measurement of pressure under the foot during function. Journal of Medical and Biological Engineering and Computing 20, 489–495 (1982)
4. Pollard, J.P., Quesne, L.P.L., Tappin, J.W.: Forces Under the Foot. Journal of Biomedical Engineering 5, 37–40 (1983)
5. Zhu, H., Maalej, N., Webster, J.G., Tompkings, W.J., Bach-Y-Rita, P., Wertsch, J.J.: An Umbilical Data-Acquisition System for Measuring Pressures Between the Foot and Shoe. IEEE Transactions on Biomedical Engineering 37, 908–911 (1990)
6. Faivre, A., Dahan, M., Parratte, B., Monnier, G.: Instrumented shoes for pathological gait assessment. Mechanics Research Communications 31, 627–632 (2004)
7. Morris, S.J.: A Shoe-Integrated Sensor System for Wireless Gait Analysis and Real-Time Therapeutic Feedback. PhD thesis, Massachusetts Institute of Technology (2004)
8. Miranda, E., Wanderley, M.: New Digital Musical Instruments: Control and Interaction Beyond the Keyboard. AR Editions (2006)
9. Papetti, S., Fontana, F., Civolani, M.: A shoe-based interface for ecological ground augmentation. In: Proc. 4th Int. Haptic and Auditory Interaction Design Workshop, Dresden, Germany, vol. 2 (2009)
10. Hollinger, A., Wanderley, M.M.: Evaluation of commercial force-sensing resistors. Unpublished report 1, Input Devices and Music Interaction Laboratory (IDMIL), Music Technology Schulich - School of Music, McGill University Montreal, QC, Canada (2006), http://www.idmil.org/publications
11. Vecchi, F., Freschi, C., Micera, S., Sabatini, A., Dario, P., Sacchetti, R.: Experimental evaluation of two commercial force sensors for applications in biomechanics and motor control. In: Proceedings of the 5th Annual Conference of the International Functional Electrical Stimulation Society, Aalborg, Denmark, p. 44 (2000)
12. Interlink: Force sensing resistor integration guide and evaluation parts catalog. Datasheet 90-45632 Rev. D, Interlink Electronics, 546 Flynn Road, Camarillo, CA 93012, USA (2009), http://www.interlinkelectronics.com/library/media/papers/pdf/fsrguide.pdf
13. Atmel: Atmega168 datasheet. Datasheet 2545RAVR07/09, Atmel Corporation, 2325 Orchard Parkway, San Jose, CA 95131, USA (2009), http://www.atmel.com/dyn/products/datasheets_v2.asp?family_id=607
14. FTDI: Data throughput, latency and handshaking. Application note AN232B-04 Rev. 1.1, Future Technology Devices International Ltd., Seaward Place, Centurion Business Park, Glasgow, G41 1HH, UK (2006), http://www.ftdichip.com/Documents/AppNotes/AN232B-04_DataLatencyFlow.pdf
15. Visell, Y., Law, A., Ip, J., Rajalingham, R., Smith, S., Cooperstock, J.R., Borin, G., Civolani, M., Fontana, F., Polotti, P., Nordahl, R., Serafin, S., Turchet, L.: Contact-based sensing methods for walking interactions. Deliverable 3.1, NIW project (2009), http://www.niwproject.eu
16. Papetti, S., Fontana, F., Civolani, M., Berrezag, A., Hayward, V.: Audio-tactile display of ground properties using interactive shoes. In: Proc. 5th Int. Haptic and Auditory Interaction Design Workshop (2010); Elsewhere in these proceedings

A Comparison of Two Wearable Tactile Interfaces with a Complementary Display in Two Orientations

Mayuree Srikulwong and Eamonn O'Neill

University of Bath, Bath, BA2 7AY, UK
{ms244, eamonn}@cs.bath.ac.uk

Abstract. Research has shown that two popular forms of wearable tactile displays, a back array and a waist belt, can aid pedestrian navigation by indicating direction. Each type has its proponents and each has been reported as successful in experimental trials, however, no direct experimental comparisons of the two approaches have been reported. We have therefore conducted a series of experiments directly comparing them on a range of measures. In this paper, we present results from a study in which we used a directional line drawing task to compare user performance with these two popular forms of wearable tactile display. We also investigated whether user performance was affected by a match between the plane of the tactile interface and the plane in which the users drew the perceived directions. Finally, we investigated the effect of adding a complementary visual display. The touch screen display on which participants drew the perceived directions presented either a blank display or a visual display of a map indicating eight directions from a central roundabout, corresponding to the eight directions indicated by the tactile stimuli. We found that participants performed significantly faster and more accurately with the belt than with the array whether they had a vertical screen or a horizontal screen. We found no difference in performance with the map display compared to the blank display.

Keywords: Evaluation/methodology, haptic i/o, user interfaces, wearable computers, pedestrian navigation.

1 Introduction

As illustrated in Table 1, researchers have proposed various forms of tactile wearable interfaces to convey directional information on different body sites. Some of these systems (e.g. [1], [2], [3]) have been tested and reported as successful in a range of environments. Of the proposed forms in Table 1, we have focused on the wearable systems that use the torso as a display site, specifically belt-type and back torso vest devices, since previous research (e.g. [4], [5]) suggests that their shape, size, and body contact areas support representation of cardinal (i.e. north, east, west and south) and ordinal (i.e. northeast, northwest, southeast, and southwest) directions and other information. We decided not to use the headband because it was reported that users had experienced discomfort wearing the system [6]. For the systems worn on wrists and feet, the size of body contact areas is too small effectively to afford the display of 8 directions. We also decided not to study the systems worn on fingers because users often require their hands to be free to perform other activities.

Table 1. Tactile wearable interfaces classified by their body contact area and form.

Body contact areas	**Forms**	**Products or Research Projects**
Head	Headband	Forehead Retina System [7], Haptic Radar [8]
Shoulders	Shoulder Pad	Active Shoulder Pad [9]
Back Torso	Vest	Tactile Land Navigation [10]
Back Torso	Chair	Haptic Back Display [4]
Back Torso	Backpack	3x3 Tapping Interface Grid [1], Personal Guidance System [11]
Around the waist	Belt	ActiveBelt [5], WaistBelt [3], [12], Tactile Wayfinder [13]
Wrist	Wristband	GentleGuide [14], Personal Guide System [15]
Fingers	Wristwatch with Finger-Braille Interface	Virtual Leading Blocks [16]
Feet	Shoes	CabBoots [2]

The physical interface layout of systems worn on the torso typically follows one of two forms: (1) a back array of vibrators generating straight-line patterns (e.g. [1], [4]); and (2) a waist belt embedded with vibrators generating absolute point vibrations (e.g. [10], [3], [5]). Researchers have reported each of these interfaces as effective.

The back array represents cardinal and ordinal directions by generating stimulation patterns on an array of vibrators to create the sensation of a dotted line, known as the "cutaneous rabbit" phenomenon [17], [4]. The tactile flow patterns, also known as saltatory signals, generated by this approach represent directions of movement [1]. Most of the wearable tactile interfaces using this approach are in the form of a vest and stimulate the user's back. Tan et al. [4], and Ross and Blasch [1] built their interfaces using a 3x3 motor array. Each direction was generated as a simulated line using three motors, e.g. vibrating motors in the middle vertical row of the array from bottom to top conveyed north. The systems were tested with drawing and street-crossing tasks. The researchers reported that tactile interaction effectively presented spatial information for the drawing tasks [4] and assisted visually impaired pedestrians in street-crossing [1].

The waist belt interface represents a direction by triggering vibration of a motor at the corresponding location around the waist. The tactile representation of absolute positions directly represents directions [3]. Van Erp et al. [3], Duistermaat [10] and Tsukada et al. [5] built prototypes in the form of a waist belt with 8 embedded motors distributed around the belt. Each motor represented one of the eight cardinal and ordinal directions, with each directional signal being generated using one motor. For example, vibrating the motor located at the front in the middle of the waist conveyed north. Evaluation results suggested that tactile interfaces were practical for conveying directional information in operational environments including pedestrian navigation during daytime [5]) and in low visibility environments such as at night [10]; navigation in visually cluttered environments, e.g. in the cockpit of an aircraft [3]; and in vibrating environments, e.g. in a fast boat [3].

These two interface designs, the back array presenting a saltatory line and the waist belt presenting absolute points, have dominated research on tactile navigation displays on the torso, with each claiming success as a navigation aid. There was, however, no reported research directly comparing performance with these two approaches. Therefore, we directly compared them in a series of experiments, one of which we report here, involving directional pointing [18] and line drawing tasks.

2 Experimental Comparison

We closely followed the designs of both established interfaces, both in the form of the wearable devices and the tactile stimuli patterns used for each. Tan et al. [4] reported that different array sizes could affect performance; specifically, smaller participants performed better with an array with an inter-motor distance of 50 mm while bigger participants performed better with a bigger array (inter-motor distance of 80 mm). Geldard et al. [17] suggests that vibrators in a back array should be spaced at least at 40 mm but no greater than 100 mm to create a saltatory signal "line effect". With little other evidence, there is no established optimum value for inter-vibrator distance. Therefore, for our initial experiments we built and tested two sizes of back array, 50 mm and 80 mm. Our 50 mm back array consisted of 9 motors mounted into a fabric pad in a 3-by-3 array. The motors had an equal inter-spacing of 50 mm. Our 80 mm back array was similar in shape but had an inter-spacing distance between motors of 80 mm. Our previous experiments [18] found the 50 mm array to be significantly less effective than the 80 mm array; therefore, in this experiment we compared only the 80 mm array and the belt. Our waist belt tactile interface consisted of 8 motors mounted in a belt. Following previous research (e.g. [3], [5]), the motors had an unequal interspacing (from 50 mm to 130 mm) to account for participants' varying body shape and size. All the interfaces were worn over light clothing such as a T-shirt.

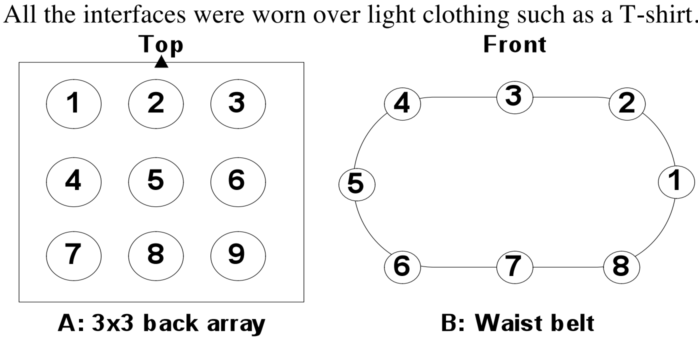


Fig 1. Layouts of the two interfaces.

The design of our tactile stimuli drew on tactile interaction design guidelines [19], the results of previous research [4] and our own pilot studies. We designed two sets of tactile stimuli: set A (Table 2) for the back array, and set B (Table 3) for the belt. Set A contained eight saltatory signals representing *east, west, south, north, southeast, southwest, northeast, and northwest*. Set B represented the same eight directions based on the location of the motors around the participant's waist, with *north* represented by front centre (i.e. motor number 3).

Table 2. Stimuli set A's signal pattern. Number in signal pattern represents motor number in Figure 1A.

Stimuli code	Signal pattern	Direction
A1	444455556666	East
A2	666655554444	West
A3	222255558888	South
A4	888855552222	North
A5	111155559999	Southeast
A6	333355557777	Southwest
A7	777755553333	Northeast
A8	999955551111	Northwest

Both sets of stimuli had the same constant frequency (200 Hz) and inter-stimulus duration (50 ms). The vibration pattern for stimuli set A involved actuation of 3 motors and consisted of 4 repetitions of signals at 50 ms pulse and inter-pulse on each motor, i.e. 12 pulses in total for each stimulus. The pattern for stimuli set B involved actuation of one motor and consisted of 12 repetitions of signals at 50 ms pulse and inter-pulse duration. Hence, the number of pulses and duration of signal were the same across both stimuli sets.

Table 3. Stimuli set B's signal pattern. Number in signal pattern represents motor number in Figure 1B.

Stimuli code	Signal pattern	Direction
B1	111111111111	East
B2	222222222222	Northeast
B3	333333333333	North
B4	444444444444	Northwest
B5	555555555555	West
B6	666666666666	Southwest
B7	777777777777	South
B8	888888888888	Southeast

2.1 Experimental Procedure

In this study, we investigated whether performance between the two wearable layouts would differ for a line drawing task. In addition, we investigated if the pointing task in our previous experiment [18] might have favoured the belt layout since the plane of the belt vibrators matched the plane of the wall sensors used for user responses. Hence, in this experiment we also varied the plane in which participants responded.

We used a line drawing task because it requires similar skills to those needed when using a map-based navigation system, e.g. the ability to interpret the understanding of directions into two-dimensional representations [20] and the ability to associate one's current view of the world to its location in the map [21]. The experimental conditions involved drawing arrowed lines, indicating perceived directions, on a touch screen with one of two orientations, vertical and horizontal. We hypothesized that participants would perform better when the plane of the prototype matched the plane of the screen, i.e. they would perform better with the back array when drawing directed lines on a *vertical* screen. On the other hand, they would perform better with the belt when the task involved drawing directed lines on a *horizontal* screen.

As Carter and Fourney [22] suggested that using other senses as cues may support tactile interaction, we introduced a visual display as an experimental factor with two levels. In the first level, the touch screen presented a blank display on which participants drew their directed line (Figure 2A). In the second level, the touch screen presented a visual display of a map indicating eight directions from a central roundabout, corresponding to the eight directions indicated by the tactile stimuli (Figure 2B). We predicted that the visual display of the map would aid the participant in interpreting and responding to the tactile stimuli.

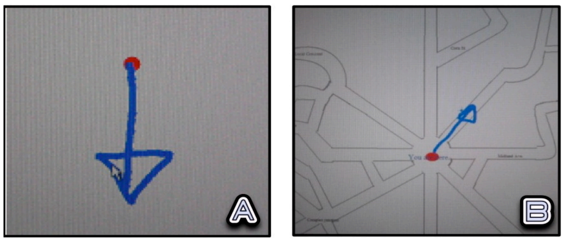


Fig. 2. A: Line drawn by a participant on the blank display. B: Line drawn by a participant on the map display.

In summary, we compared performance with the array and belt tactile interfaces and the effect on performance of (1) the plane of output display and (2) the presence or absence of a visual map display. The experimental hypotheses were as follows.

H1. Performance will be better when the plane of the tactile stimuli matches the plane of the responses, specifically:

H1a. Participants will perform better with the back array when the task involves drawing lines on a vertical screen;

H1b. Participants will perform better with the waist belt when the task involves drawing lines on a horizontal screen;

H2. Participants will perform better with the map display than the blank display.

There were 16 participants, 7 males and 9 females, with an average age of 29. Participants reported no abnormality with tactile perception at the time of experiment. They had no previous experience with tactile interfaces. They understood the concept of "direction" and were able to draw all cardinal and ordinal directions. Participants used both tactile interfaces. They were instructed to stand at a marked point approximately 200 mm away from the screen in the vertical display condition; and 130 mm away from the lower edge of the screen in the horizontal display condition. The height of the screen was adjusted to suit individual participants for the vertical and horizontal conditions. The order of conditions was counterbalanced.

There were 8 conditions, as shown in Table 4. Participants responded to the directions they perceived by drawing arrows with a stylus on the touch screen. Each participant responded to 8 stimuli in each condition. We compared a range of performance measures: time between the end of each stimulus and the response (response time), correctly perceived directions (accuracy), failure to identify any direction for a stimulus (breakdown), and incorrectly identified directions (error).

Participants were given a demonstration of how they would receive tactile stimuli via each prototype but were given no other training. We wanted to discover how well they could intuitively (i.e. without extensive training) interpret the meanings of different tactile patterns and to discover how usable the interfaces were without training. A key factor to successfully introducing new technology lies in its usability. Novel consumer technologies typically come with little or no training.

Table 4. Experimental conditions and their codes.

Back Array				**Waist Belt**			
Vertical screen		**Horizontal screen**		**Vertical screen**		**Horizontal screen**	
Blank (C1)	Map (C2)	Blank (C3)	Map (C4)	Blank (C5)	Map (C6)	Blank (C7)	Map (C8)

2.2 Results

2.2.1 Overall accuracy and response time analysis

The mean accuracy, error, breakdowns and response times for the back array and the belt are shown in Tables 5 and 6. The data were analyzed using a three-way repeated-measures ANOVA with *tactile interface*, *screen orientation* and *visual display* (Table 4 top, second and third rows respectively) as the independent variables. There was no significant interaction effect between *tactile interface* and *screen orientation* on accuracy ($f_{1,15}$ = 0.54, n.s.), errors ($f_{1,15}$ = 0.05, n.s.), breakdowns ($f_{1,15}$ = 1, n.s.) or response time ($f_{1,15}$ = 1.74, n.s.). These results tell us that the effects of the different tactile interfaces did not vary depending on the touch screen's orientation, horizontal or vertical.

Table 5. Mean performance for vertical screen conditions. *Scores: n of 8, Time: in seconds. SDs in parentheses.*

	Back Array *Vertical* **Screen**		**Waist Belt** *Vertical* **Screen**	
	Blank (C1)	**Map (C2)**	**Blank (C5)**	**Map (C6)**
Accuracy	5.06 (1.84)	5.25 (1.65)	7.44 (0.63)	7.19 (1.11)
Error	2.81 (0.63)	2.44 (1.59)	0.50 (0.63)	0.75 (1.07)
Breakdown	0 (0.00)	0.31 (0.60)	0 (0.00)	0.06 (0.25)
Time	2.13 (0.50)	2.08 (0.83)	1.40 (0.37)	1.54 (0.67)

Post hoc Bonferroni pairwise comparisons showed that accuracy was significantly better with the belt than with the array in every case ($p < 0.002$); errors were significantly fewer with the belt than with the array in every case ($p < 0.002$); and response time was significantly quicker with the belt than with the array in every case ($p < 0.002$). No significant difference was found for breakdowns.

Table 6. Mean performance for horizontal screen conditions. *Scores: n of 8, Time: in seconds. SDs in parentheses.*

	Back Array *Horizontal* **Screen**		**Waist Belt** *Horizontal* **Screen**	
	Blank (C3)	**Map (C4)**	**Blank (C7)**	**Map (C8)**
Accuracy	5.63 (1.75)	5.63 (1.67)	7.5 (0.63)	7.63 (0.89)
Error	2.25 (1.65)	2.31 (1.66)	0.44 (0.63)	0.25 (0.58)
Breakdown	0.12 (0.34)	0.06 (0.25)	0 (0.00)	0.12 (0.50)
Time	2.08 (0.37)	2.21 (0.59)	1.28 (0.35)	1.41 (0.36)

Hypothesis H1 was rejected since participants performed significantly faster and more accurately with the belt than with the array whether they had a vertical screen or a horizontal screen.

A three-way repeated-measures ANOVA was run to compare blank displays and visual map displays on accuracy, response time, breakdowns and errors. No significant effect of display type was found on accuracy ($f_{1,15} = 0.01$, n.s.), response time ($t_{1,14} = 0.06$, n.s.), breakdowns ($t_{1,15} = 2.56$, n.s.), or errors ($t_{1,15} = 0.14$, n.s.). Thus, we rejected hypothesis H2 since display type had no effect on performance.

2.2.2 Accuracy and response time by stimulus

We performed further analysis on accuracy and response times with respect to the stimuli. Using the array, participants performed worst in accuracy (C1 and C2 in Figure 3, and C3 and C4 in Figure 4) with vertical (*north* and *south)* and horizontal saltatory signals (*east* and *west*). The inaccuracy ranged widely from 45 to 180 degrees (both to the left and to the right of intended directions). Figure 5 also shows that participants responded much more slowly with the array than with the belt in all directions. They were slowest with the *north* signal. Using the belt, there was no significant difference in participants' accuracy and response times with different stimuli. Almost all incorrect answers were 45-degree errors.

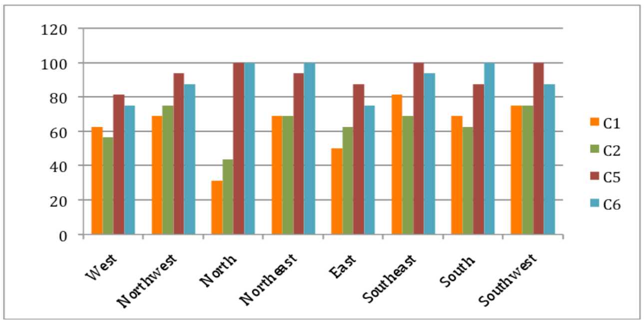


Fig. 3. Accuracy of responses (%) for all directions with the vertical screen conditions.

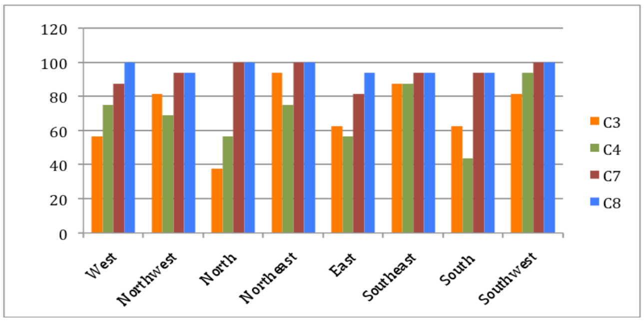


Fig. 4. Accuracy of responses (%) for all directions with the horizontal screen conditions.

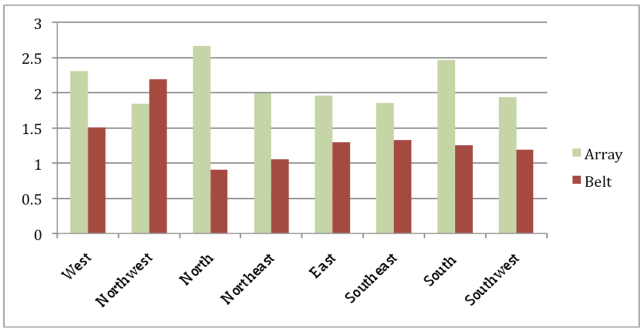


Fig. 5. Average response time (in second) for array conditions (C1 – C4) and belt conditions (C5 – C8).

3 Conclusion

Two types of wearable tactile displays, back array and waist belt, have been reported as successfully representing direction in experimental trials, however, previous research has not directly compared their performance. Our experiments reported here and in [18] show the belt to be significantly better than the array across a wide range of conditions, in this study regardless of screen orientation or visual display.

The experiment reported here also suggests that the visual display of the directions (in the map condition) did not aid the perception of and response to the tactile stimuli. This offers support to the notion that a unimodal tactile system, such as the tactile navigation aids presented by Tan et al. [4] and Van Erp et al. [3], is feasible without support from other modalities such as visual displays. It does not, however, rule out the possibility that other complementary displays might provide such aid.

Overall, our results suggest that the belt is a better choice for wearable tactile direction indication than the back array, however, our experiments did not seek to tease out which particular features of these two established approaches led to the observed differences. The two approaches actually vary on at least three potentially significant features: physical layout of vibrators, stimuli patterns (tactile flow *vs* absolute point), and body contact areas. We have found no published research that attempts to systematically vary these three features. In the experiment reported here, we have shown that the belt is more effective than the array in the form in which each of these designs has most commonly been realized. We did not examine the effects of more extensive training or long-term use. Other studies will be required to investigate these effects, which might help to improve the performance of the back array.

Acknowledgements. Mayuree Srikulwong's research is supported by the University of Thai Chamber of Commerce, Thailand. Eamonn O'Neill's research is supported by a Royal Society Industry Fellowship at Vodafone Group R&D.

References

1. Ross, D.A. and Blasch, B.B.: Wearable Interfaces for Orientation and Wayfinding. In: 4th International ACM Conference on Assistive Technologies (ASSETS '00), pp. 193-200 (2000)
2. Frey, M.: CabBoots – Shoes with Integrated Guidance System. In: 1st International Conference on Tangible and Embedded Interaction (TEI'07), pp. 245-246 (2007)
3. Van Erp, J.B.F., Van Veen, H.A.H.C., Jansen, C. and Dobbins, T.: Waypoint Navigation with a Vibrotactile Waist Belt. ACM Transaction of Applied Perception, 2, 2, pp. 106-117 (2005)
4. Tan, H.Z., Gray, R., Young, J.J. and Traylor, R.: A Haptic Back Display for Attentional and Directional Cueing. Haptics-e: The Electronic Journal of Haptics Research, 3, 1 (2003)
5. Tsukada, K. and Yasumura, M.: ActiveBelt: Belt-type Wearable Tactile Display for Directional Navigation. In: 6th International Conference on Ubiquitous Computing (UbiComp '04). LNCS 3205, pp. 384-399 (2004)

6. Myles, K., and Binseel, M.S.: The Tactile Modality: A Review of Tactile Sensitivity and Human Tactile Interfaces. U.S. Army Research Laboratory, ARL-TR-4115, Aberdeen Proving Ground, MD 21005-5425, (2007)
7. Kajimoto, H., Kanno, Y., and Tachi, S.: Forehead Retina System. In: 33rd International Conference On Computer Graphics and Interactive Techniques (2006)
8. Cassinelli, A., Reynolds, C., and Ishikawa, M.: Augmenting Spatial Awareness with Haptic Radar. In: 10th International Symposium on Wearable Computers (ISWC'06), pp. 61-64 (2006)
9. Toney, A., Dunne, L., Thomas, B.H. and Ashdown, S.P.: A Shoulder Pad Insert Vibrotactile Display. In: 7th IEEE International Symposium on Wearable Computers (ISWC'03), pp. 35-44 (2003)
10. Duistermaat, M.: Tactile Land in Night Operations, TNO-Memorandum TNO-DV3 2005 M065. TNO, Soesterberg, Netherlands (2005)
11. Loomis, J.M., Golledge, R.G., and Klatzky, R.L.: GPS-based Navigation Systems for the Visually Impaired. In: Barfield, W., Caudell, T. (eds.) Fundamentals of Wearable Computers and Augmented Reality, pp. 429-446. Lawrence Erlbaum, Mahwah, NJ (2001)
12. Ho, C., Tan, H.Z., and Spence, C.E.: Using Spatial Vibrotactile Cues to Direct Visual Attention in Driving Scenes. Transportation Research Part F 8: Traffic Psychology and Behavior, pp. 397-412 (2005)
13. Heuten, W., Henze, N., Boll, S., and Pielot, M.: Tactile Wayfinder: a Non-Visual Support System for Wayfinding. In: 5th Nordic Conference on Human-Computer Interaction: Building Bridges (NordiCHI'08), vol. 358, pp. 172-181 (2008)
14. Bosman, S., Groenedaal, B., Findlater, J.W., Visser, T., De Graaf, M., and Markopoulos, P.: GentleGuide: An Exploration of Haptic Output for Indoors Pedestrian Guidance. In: 5th International Symposium on Human Computer Interaction with Mobile Devices and Services (Mobile HCI'03), pp. 358-362 (2003)
15. Marston, J.R., Loomis, J.M., Klatzky, R.L. and Golledge. R.G.: Nonvisual Route Following with Guidance from a Simple Haptic or Auditory Display. Journal of Visual Impairment and Blindness, vol. 101, pp. 203-211 (2007)
16. Amemiya, T., Yamashita, J., Hirota, K., and Hirose, M.: Virtual Leading Blocks for the Deaf-Blind: A Real-Time Way-Finder by Verbal-Nonverbal Hybrid Interface and High-Density RFID Tag Space. In: IEEE Virtual Reality Conference 2004 (VR'04), pp. 165-172 (2004)
17. Geldard, F.A. and Sherrick, C.E.: The Cutaneous 'Rabbit': A Perceptual Illusion. Science, 178, 4057, pp. 178-179 (1972)
18. Srikulwong, M. and O'Neill, E.: A Direct Experimental Comparison of Back Array and Waist-Belt Tactile Interfaces for Indicating Direction. In: Workshop on Multimodal Location Based Techniques for Extreme Navigation at Pervasive 2010, pp. 5-8 (2010)
19. Van Erp, J.B.F.: Guidelines for the Use of Vibro-Tactile Displays in Human Computer Interaction. In: EuroHaptics 2002, pp. 18-22 (2002)
20. Yao, X., and Fickas, S.: Pedestrian Navigation Systems: a Case Study of Deep Personalization. In: 1st International Workshop on Software Engineering for Pervasive Computing Applications, Systems, and Environments (SEPCASE '07), pp. 11-14 (2007)
21. Aretz, A.J.: The Design of Electronic Map Displays. Human Factors, 33, 1, pp. 85-101 (1991)
22. Carter, J. and Fourney, D.: Research Based Tactile and Haptic Interaction Guidelines. In: Guidelines on Tactile and Haptic Interaction (GOTHI 2005), pp. 84-92 (2005)