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Natural Interactive Walking

Deliverable 2.1

Haptic Device Engineering for Walking Interactions

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Contents

1 Introduction to Deliverable 2.1 1

2 Haptic Engineering: Shoes (UPMC) 3
2.1 Introduction . . . 3
2.1.1 Technical Challenge . . . 3
2.2 Temporal Layer . . . 4
2.2.1 Structural design prototype . . . 5
2.2.2 New high-performance recoil actuators . . . 6
2.2.3 Completed design . . . 7
2.2.4 Completed design . . . 7
2.2.5 Other design under development . . . 8
2.3 Spatial Tactile Display Layer . . . 8

3 Vibrotactile Display via Rigid Floor Tiles (McGill University) 9
3.1 Preface and Outline of the Contents . . . 9
3.2 Design approach . . . 9
3.3 Distributed floor interface . . . 10

1 Introduction to Deliverable 2.1

Deliverable 2.1 consists of "Initial device designs and prototypes for haptic interaction in walking", associated to Task 2.2 ("Haptic Display Methods") of Work Package 2.

The Work Package objectives (Annex 1, page 29) relevant to this deliverable are: "To identify new methods for low-cost haptic interaction in walking, exploiting novel perceptual illusions and cross-modal effects where suitable. To create prototype interactive devices based on these methods."

The present documentation provides details concerning the new device designs, and summarizes the prototypes that have been produced. Two main approaches have been adopted. The first concerns the development of wearable haptic interfaces for the feet ("haptic shoes") capable of reproducing aspects of the signals arising during walking on natural ground surfaces, especially those most salient to tactile perception. Separate consideration has been given to exploiting temporal and spatial information channels, with separate design aspects being influenced by each channel. This work is reviewed in Section 1.

The second approach to the design of low-cost haptic displays for natural interactive walking has focused on actuated floor surfaces. The devices developed are employed for the interactive display of vibrotactile signals similar to those arising from foot-ground contact during walking (with shoes) on natural surfaces. As the spatial scale of this device is approximately that of the whole foot, it conforms more closely to the temporal information display paradigm noted above. Work in this area is reviewed in Section 2. The technical content is included in a companion manuscript (currently under review), which is linked from the deliverable text but not directly included in this public deliverable due to copyright restrictions.

2 Haptic Engineering: Shoes (UPMC)

2.1 Introduction

This section of the deliverable describes research aimed at designing footware capable of providing a wide array of tactile sensations of interest in virtual reality and other applications. The design of such items is challenging given that the targetted item should function as soles or shoes, that is, permit a person to walk and be resistant and flexible enough to support her or his weight but at the same time integrate actuation. Since actuators tend to be bulky and heavy, designs must be found such that the actuators can be miniaturized, optimaly coupled to the sensitive cutaneous and subcutaneous tissues. Clearly we are in the presence of conflicting requirements where structural strength opposes freedom of movement.

The achievement of these goals will open up a wide array of applications including:

- Simulation of walking grounds: If certain key aspects of the shoe-ground interaction can be reproduced artificially, then the illusion of walking on virtual grounds can be given in virtual reality settings;
- Simulation of interaction with certain materials: Certain qualities of materials can be reproduced in order sensations simular to when interacting with these materials in settings other than virtual reality;
- Vehicle simulation: Most vehicles such as cars, boats and planes give vibrations through the feet. In simulators for such vehicles realism could be enhanced.

Beside simulation of environments or specific interactions, the delivery of tactile stimulation in shoe soles can also be used in:

- Sports training: Applications could include pace makeing signals to the feet, enhancement of vibration to warn about conditions such as slip;
- Rehabilitation computer controller foot stimulation can be applied to mitigate sensory deficits through stochastic resonance and activation-based learning.
- Scientific experiments to investigate perceptual functions of the nervous system and its effects on motricity and balance.

2.1.1 Technical Challenge

The design problem can be stated informally as “making louspeakers you can walk on and that you can wear”. The haptic system — the foot is no exception — is sensitive to high resolution spatial and temporal signal variations. The haptic system may view it like a hybrid between vision and hearing, having the capabilities of neither but combining some of each.

The general design philosophy is to first to provide actuators capable of broadband, distorsion-free transduction, leaving to the software the responsability of shaping the signals, entertaining the same relationship to the software than acoustic transducers would. Such transducers, however, are not commercially available and therefore must be designed with a size, form factor, power and bulk compatible with their inclusion into a shoe. Another basic properties of the actuators is to be able able to resist crushing if the sole design is such that they are likely to need to resist to the load of a

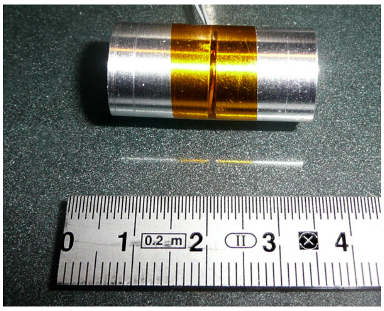

Figure 2.1: Example of self-contained recoil-type actuator used in this project specifically designed and manufactured by Tactile Labs Inc.

person. An example of such actuator of the recoil-type is shown in Figure 2.1 and further discussed later.

The second design problem is the structural properties of the sole. In the in fact a technical precedent to our problem. It comes from seismic isolation technology. While the connection may not be evident at forst sight it can be seen that seismic isolstion blocs for buildings accomplish the same function as our desired soles. The most destructive components in earthquake tremous are shear waves. To isolate bulidings from these perturbations, it is needed to engineer structural components that are elastic in shear deformation but strong and stiff when loaded vertically.

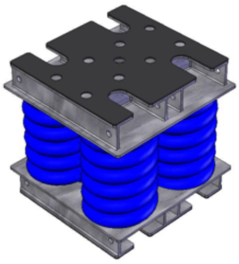

Figure 2.2: Example of seismic isolation structural component. It is made of stacked elastomneric liquid-filled tori that provide specific elasticity in the shear direction and sturctural strength in the vertical direction.

The design of active soles must therefore account for these properties. Since no tranducer technology can cater to both the spatial and temporal requirements of touch (especially when stressing the transducer with 80 kg of static load), we must resort of a collection of tricks. Chiefly among them is the idea to separate out the spatial from the temporal aspects of the signal to transduce in designs that feature two layers that can be used in isolation or combine according to the application.

2.2 Temporal Layer

The temporal layer is reponsible for providing broadband stimulation to foot. It is made of two component, a structural component and actuation. In this section, we first describe an engineering prototype designed to validate the operation of an advanced active shoe. We then describe a simpler, lower performing, design based on commercially available components.

2.2.1 Structural design prototype

Refering to Figure 2.3, a sole structural design is shown (just for the heel). The bottom layer is to be made of molded rubber shaped as to be compliant in the sagittal direction but stiff in the vertical and in the lateral directions. Using finite element simulations, the design strategy is to achieve a compliance that is as close as possible to the shear stifness of a typical heel. This requirement is motivated by the desire to couple the sole to the foot optimally from the view point of vibration transmission, since a source and a load of commensurate impedances would be coupled. The actuators, which for validation purposes are disposed on the sides, are described next. A possible active shoe design with four actuators is shown in Figure 2.4.

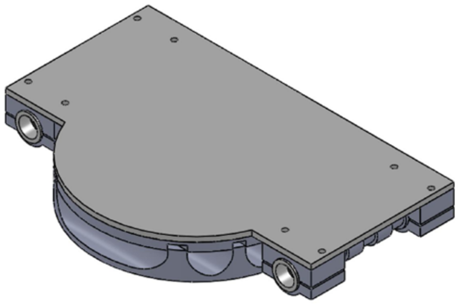

Figure 2.3: Heel component.

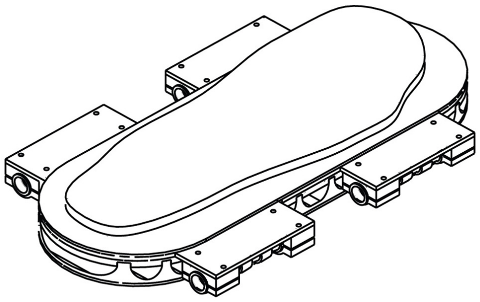

Figure 2.4: Structural sole.

Before committing to a manufacturing cycle, an engineering prototype was built and tested. Triangular section of high performance elastomere were design and mounted as shown in Figure 2.5. Their section was optimized such that those supports would not buckle under arbitrarily large loads and yet conserve a constant shear stiffness regardless of the load. They are shown here during testing.

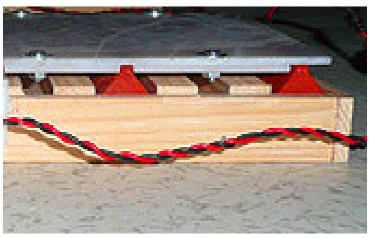

Figure 2.5: Compact structural elastomeric elements able to resist large vertical loads and yet remain compliant lateral independently from the load.

Figure 2.6 shows an implemented protype which now in used in the lab to carry out characterization. It is also used to run pilot scientific experiments related to the perceptual effects of foot stimulation.

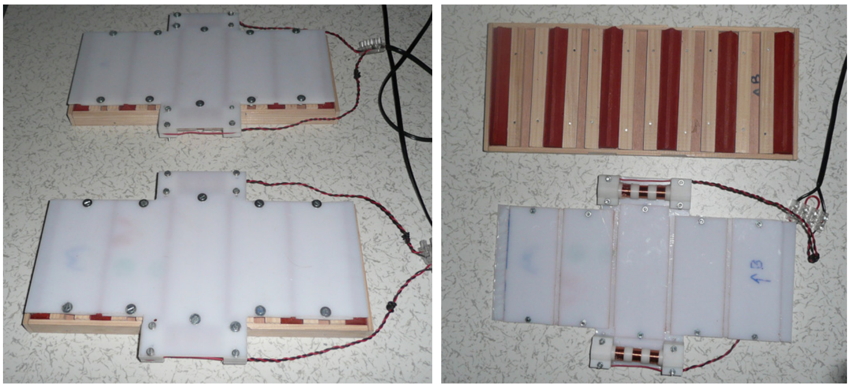

Figure 2.6: Sole prototype with only two actuators. Left: pair of soles that can be stepped on. Middle: sole opened to show the structural design. Right: side view to show that this design can be made compatible with the geometry of an ordinary shoe.

2.2.2 New high-performance recoil actuators

A new generation of recoil-type actuators was designed. They are iron-less and omit the use of soft iron magnetic return. They also integrate an optimized multiple magnet configuration.

As in our prior designs, the magnetic slug is suspended between two membranes with pins shaped to ensure soft bottoming in case of saturation in the low frequencies and to prevent actuator self-destruction.

The passband of this system is 40 to 10 kHz and consumes less than 10 W of power to produce thrust up to 7 N, resulting very high accelerations. The optimal geometry was determined from extensive magnetic CAD simulations (Comsol Inc.). They achieve a Bl factor of roughly 10 Tm which is equivalent to high-end woofers having metalic parts (magnets and soft iron) of a mass of the order of 1 000 g).

This shows the very high efficiency that iron-free actuators can achieve with careful design. It is evident convential voice-coil designs could not be embedded in soles where our prototypes are in fact very close to have a form factor and a mass compatible with ordinary soles.

2.2.3 Completed design

In order to deliver working system to the partners, we also build active shoes from commercial components. Their performance is however restricted in bandwidth and intensity of sensation that they can deliver.

Figure 2.9 shoe a commercial sandal with the miniature actuators embedded in the foam of which they are made. These models were selected for the properties of rubber foam material of which they are made, which is light and stiff and hence promotes the propagation of vibrations. The efficiency is however not nearly as great as the custom made soles.

Pairs have been delivered to AAU and UNIVR before or during the 2009 annual meeting.

2.2.4 Completed design

Figure 2.9 shows another design of a custom-adjustable sole where the actuators are recessed in cavities such that the sole itself can support the weight of the wearer and the actuators are suspended in elastic craddles in contact with the skin. This design is very simple and very efficient (since the active surface do not bear weight) but cannot accommodate the spatial-temporal tranducer combination. It is powered by custom-made (Tactile Lab Inc.) miniature actuators shown in the same figure.

Figure 2.7: Active shoe (exploded to expose the actuators) made of commercial components.

2.2.5 Other design under development

We are also experimenting with an alternate approach to decouple stimulation from structural support.

The idea is to recess the actuators in cavities in the soles such that the cavities are small enough to permit normal standing and walking. The actuators are spring loaded upward to contact the feet directly through specifically engineered surfaces. In this fashion, they are not subject to the load of the weight of the user.

A preliminary concept is hown in Figure 2.10.

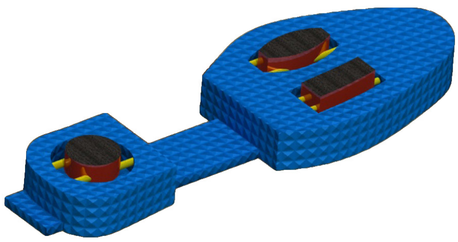

Figure 2.8: Active sole with spring-loaded recessed actuators.

2.3 Spatial Tactile Display Layer

Finally as discussed in the Introduction we are building a foot tactile display that is rigid and in direct contact with the skin (or through a sock) features in our initial design 700 “one-bit” actuators, that is, the system has high spatial resolution (relatively to the foot innervation) but can only display simple waveforms and patterns.

Figure 2.11 shows the design of the upper plate routing the signals to the actuators. A lower layer supports distributed electronics to activate the actuators. Each actuator comprise a miniature coil (off-the shelf) and a magnet sliding in tubular receptable and hence is only made of three parts. This way it possible to obtain a spatial density of actuators which is compatible with the spatial discrimination perfomance of the human foot.

It is expected that such system coupled with the high temporal resolution stimulation will make it possible to deliver a large number of tactile stimuli spanning a rich domain.

Figure 2.9: Signal routing upper board of the Spatial Tactile Display Layer.

3 Vibrotactile Display via Rigid Tiles (McGill)

3.1 Preface and Outline of the Contents

This section of the deliverable details research in the Shared Reality Environments Lab at McGill University on the optimized redesign of a vibrotactile display device, consisting of a floor tile component with integrated vibrotactile display capabilities, building on prior prototyping activities by the same researchers [2, 1].

The sections below provide a brief summary of work on the design of the tile interface and distributed systems of such tiles. The technical content is presented in detail in a report that is included in the supplementary materials for this deliverable (available from the project website or at the internet URL below). As the report itself is submitted for blind peer review to a pertinent academic conference, it is not included here, for copyright reasons.

3.2 Design approach

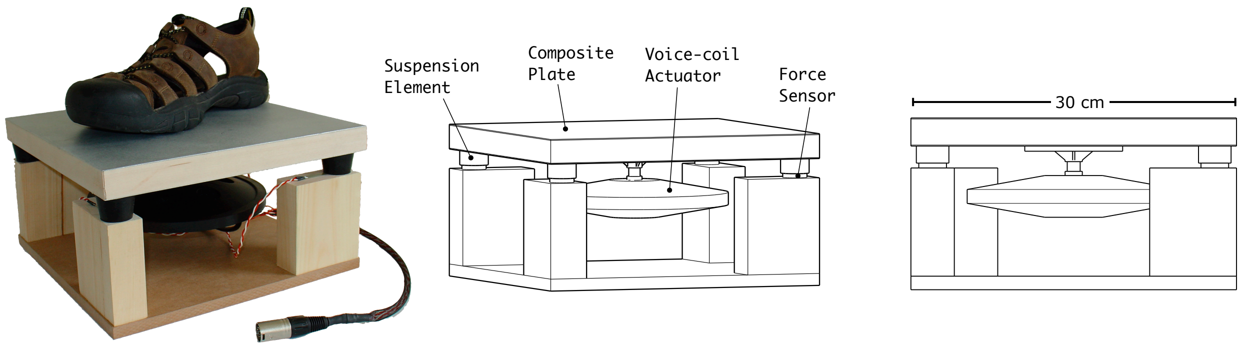

Figure 3.1: Vibrotactile floor interface hardware for a single tile unit. Left: Photo with large mens' shoe, showing representative size. The model shown is based on the low-cost force sensing resistor option. The cable in the foreground interfaces with the sensors. Middle: View showing main components. Right: Side view with top dimension.

The second approach to the design of low-cost haptic displays for natural interactive walking has focused on actuated floor surfaces. The devices developed are employed for the interactive display of vibrotactile signals similar to those arising from foot-ground contact during walking (with shoes) on natural surfaces. As the spatial scale of this device is approximately that of the whole foot, it conforms more closely to the temporal information display paradigm noted above. Work in this area is reviewed in Section 2. The technical content is included in a companion manuscript (currently under review), which is linked from the deliverable text but not directly included in this public deliverable due to copyright restrictions.

The design approach is based on the augmentation of floor tiles, otherwise similar to those familiar to many everyday environments, with electronic components that transform them into interactive haptic displays. The tiles use low-cost, low-power vibrotactile actuators. The model can be considered to that of haptic force display without the DC (0 Hz) component. In previous work, we established that high frequency forces, sensed through the human tactile channel, carry much of the information salient to the identity of the materials covering common ground surfaces.

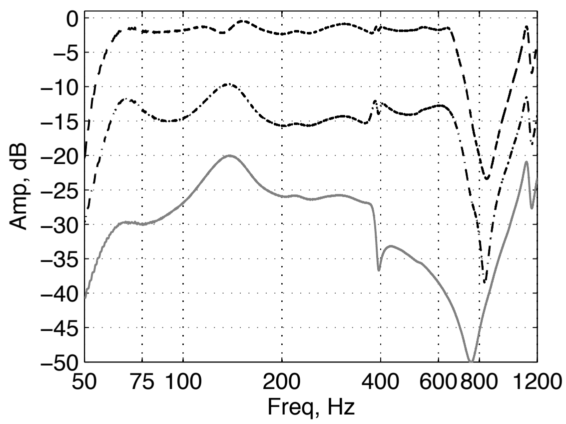

Figure 3.2: Lowest curve: Measured device frequency response without foot contact. Middle: Same response after correction by an IIR filter of order $N = 10$. Top: Response corrected with filter of order $N = 14$. The plotted amplitudes are offset for clarity of presentation. The y-axis labels (in dB) are intended to indicate variation rather than absolute amplitude.

The referenced report describes in detail the analysis, optimized redesign and evaluation of this high fidelity vibrotactile display system. The device consists of a light, composite plate mounted on an elastic suspension with integrated force sensors, and actuated by a single voice coil motor (Fig. 3.1). The structural dynamics of the device were optimized during the course of this research, within the constraints imposed by the requirements of user interaction, and were further compensated via digitally implemented inverse filtering. Measurements of the resulting display demonstrate that it is capable of accurately reproducing forces of more than 40 N across a frequency band ranging from 50 Hz to 750 Hz (Fig. 3.2).

The spatial scale of the device (Fig. 3.1) has been designed to reflect the emphasis on temporal cues: It is required only to be small enough so as to effectively separate the feedback supplied to each foot. A uniform feedback is supplied across the surface of the tile interface.

3.3 Distributed floor interface

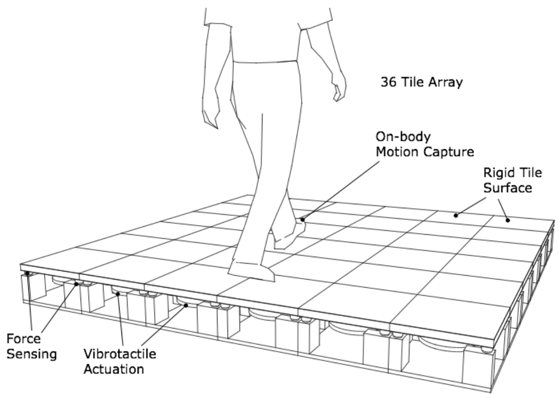

Figure 3.3: Distributed floor interface as installed in the authors' laboratory. Left: Photo showing the floor interface as situated within an immersive, rear projected virtual environment simulator. Right: illustration showing both sensing and actuating components.

The second approach to the design of low-cost haptic displays for natural interactive walking has focused on actuated floor surfaces. The physical interface in this case consists of an array of networked, rigid floor tiles, designed in the same way as the unitary tile described above, and distributed over an area of several square meters within a CAVE-like virtual environment simulator (Fig. 3.3).

A second focus of the work on distributed floor interfaces is the parsimonious use of contact information captured through the force sensors of multiple tiles for interaction with augmented floor surfaces. The basic element of information captured is the contact centroid. It provides an efficient local summary of the foot-floor interaction. As we demonstrate in Deliverable 3.1, it can conveniently be utilized to channel interaction with a virtual deformable ground surface, providing plausibly realistic visual, auditory, and tactile feedback, or for selection and operation of a floor based multimodal control interface.

Details on this design are included in Deliverable 3.1, and the technical content is included in a companion manuscript (currently under review), which is linked from the deliverable text but not directly included in this public deliverable due to copyright restrictions.

Supplementary materials for this section

The supporting materials on the design of the vibrotactile display device referenced above can be downloaded from the project website, under supporting materials for Deliverable 2.1, or from the following internet URLs:

`http://www.cim.mcgill.ca/~yon/NIW/D2.1/NiwSreTileDeviceDraft.pdf`

References

[1] AW Law, BV Peck, Y. Visell, PG Kry, and JR Cooperstock. A multi-modal floor-space for displaying material deformation underfoot in virtual reality. In *Proc. of the IEEE Intl. Workshop on Haptic Audio Visual Environments and Their Applications*, 2008.

[2] Y. Visell, J.R. Cooperstock, B.L. Giordano, K. Franinovic, A. Law, S. McAdams, K. Jathal, and F. Fontana. A Vibrotactile Device for Display of Virtual Ground Materials in Walking. *Lecture Notes in Computer Science*, 5024:420, 2008.