A Vibrotactile Device for Display of Virtual Ground Materials in Walking

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Abstract. We present a floor tile designed to provide the impression of walking on different ground materials, such as gravel, carpet, or stone. The device uses affordable and commercially available vibrotactile actuators and force sensors, and as such might one day be cost-effectively used in everyday environments. The control software is based on a lumped model of physical interactions between the foot and the ground surface. We have prototyped a measurement scheme for calibrating the device to match real-world ground materials.

1 Introduction

In a 1939 paper, J. A. Hogan describes an incident in which Marcel Proust entered the courtyard of the Princess de Guermantes' residence in Paris when "his feet came to rest on two uneven flagstones, and as he balanced from one to the other a delicious sensation swept through his body" (Hogan, 1939). The author continues, "How came he by these sensations? ... Suddenly it was revealed to him. It was Venice. One day, long since past, he had stood in the baptistry of St. Mark's in Venice, balanced on two uneven flagstones."

The interactive device we present here was motivated by the idea that a simplified audio-haptic stimulation, delivered to a walking user, might successfully evoke real-world materials provided certain of their features are preserved. Proust's experience with the flagstones in Paris provides a literary example of the power of such associations.

The tiles we are developing explore the extent to which pedestrians can be provided with the illusion that they are walking on materials such as gravel, earth, or pavement, through the interactive variation of a vibrotactile signal delivered to the feet via the surface of a floor tile (Figure 1). Prior research has addressed the rendering of virtual haptic surface textures by means of manually operated haptic devices, and similar information is often conveyed via non-force reflecting vibrotactile feedback.

Significant attention has also been devoted to the development of virtual haptic locomotion interfaces (overviewed in [6]). Some of these, such as the HapticWalker [10], have aimed to represent the shape of the ground (stairs, inclines, or irregular surfaces) during locomotion. However, such devices have characteristically provided an unfamiliar and compliant surface feel. Our tiles are meant to provide a simpler and lower-cost alternative to haptic locomotion devices, and perhaps to furnish information complementary to what they offer.

To date, less effort has been dedicated to representing the rich array of material textures that are explored via the feet during walking, despite the fact that aesthetically and informatively designed ground materials have long played a role in urban environments, parks, and buildings. A second motivation for the approach described here is that the tiles concerned may one day be seamlessly and cost-effectively applied in such contexts.

Our work draws on physically based sound synthesis models of contact interactions between the feet and the floor [2, 3]. Due to the common physical origin of the stimuli, such models can also be used to generate vibrotactile cues. Haptic rendering methods for simulation of low-level physical phenomena, such as impacts, friction, or rolling, have more commonly been applied to manual interaction with virtual environments (as overviewed in [5]).

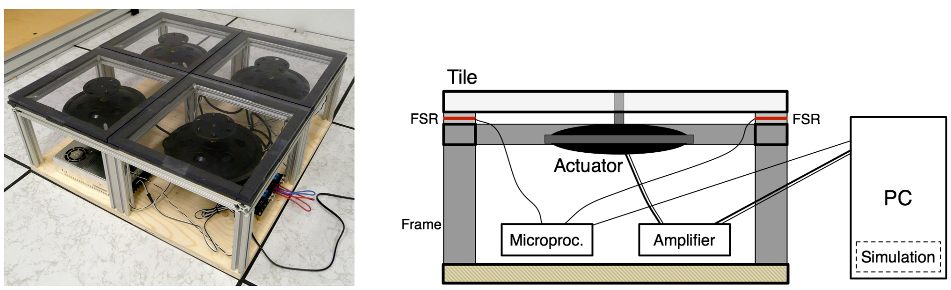

Fig. 1. Left: An image of the tile prototype, showing the tile surface (polycarbonate sheet), vibrotactile actuator, force-sensing resistors, structural frame, and associated electronics. Right: Diagram of the same, including the PC running the floor material simulation.

Identification of Ground Materials in Walking The feet may be seen as well suited to the display of ground textures, because of the high density of tactile mechanoreceptors in the soles. However, whether people are able to use such tactile information to identify the materials they are walking on is less obvious. This question motivated recent experiments carried out by the authors [4] to measure subjects' abilities to perform such identification tasks, and to assess subjects' use of haptic, proprioceptive, and auditory information in ground material identification. The materials included both solids (e.g. marble) and aggregates (e.g. gravel or sand). Subjects were able to discriminate between very similar materials (such as gravels of similar coarseness) at highly significant levels, by walking on them. Prior research has explored how material properties of objects are perceived from their acoustic signatures when struck [9]. Lederman and her colleagues have studied how well textured surfaces explored with a probe are discriminated using haptic and/or auditory information [7].

2 Device Design and Methodology

The current device design (Figure 1) consists of $12 \times 12 \times 0.5$ inch polycarbonate tile affixed to dense foam supported by a structural frame. A powerful linear motor actuator (Clark Synthesis model TST-Silver) is bolted via a steel plate to the underside of each tile. This actuator has a frequency response that extends from about 10 Hz to 18 kHz. Force sensing resistors (Interlink model 402) are encased in the layer of foam between the supporting structure and the tile surface. The sensor signals are conditioned, then digitized by a microprocessor board (Atmel AVR ATmega128). A serial data link transmits the data to a software simulation, described below, which is hosted by a real-time computing environment (Cycling'74 Max/MSP). The simulation generates independent audio signals for each tile. These signals are used to drive each actuator, via a 100 W / channel, class-D audio amplifier. The system is controlled in open-loop fashion. The input-output latency is less than 20 ms, which is adequate for aggregate material simulations, but marginal for solids. The device produces vibrotactile stimuli, as well as auditory stimuli that are respectively transmitted and radiated by the vibrating surface of each tile.

Auditory and haptic stimuli are generated continuously in response to users' footsteps using physically based synthesis algorithms originally designed for sound. Here, we briefly describe the aggregates model that is used to simulate snow, gravel, sand and similar materials. The model has been described in more detail elsewhere [3, 11]. Its main features are a stochastic process governing the production of microscopic impacts, characterized by a mean rate $N(t)$, a nonlinear impact model, and a model for the dispersion of excitations in the medium. A set of parameters governs the virtual material, including stiffness and resonant modes.

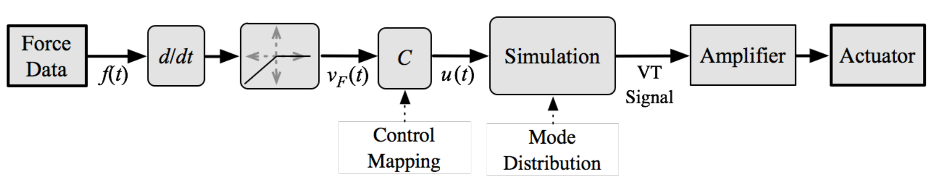

Fig. 2. Interactive system for aggregate ground material simulation, including the control mapping C, crumpling model, and display actuator.

In the tile device, the synthesis control signal $u(t)$ is derived from an excitation signal v_F given by the half-wave rectified rate of change in the force $F(t)$

applied to the tile,

$$v_F(t) = -dF/dt \ \text{ if } dF/dt < 0 \quad \text{and 0 else} \tag{1}$$

Based on the analysis explained below, we infer that the material response can be explained, to a first approximation, by a control mapping C that is a linear function of this input, so that $u(t) = \alpha\, v_F(t)$. The result is that, as expected, the simulation only responds when the user increases pressure on the tile (steps downward onto it).

2.1 Measurement of Ground Surfaces and Device Calibration

The parameters of the rendering algorithms can be tuned by hand to intuitively approximate the feel of natural materials. However, because of the number of parameters involved, and the unknown nature of the control mapping, a method for determining these settings from data characterizing real-world materials is desirable.

We have prototyped an approach to this calibration problem. It involves (1) Data characterizing the real-world interactions of interest, such as the force applied to the ground and the vibrational and acoustic responses that result; (2) An algorithm for determining the optimal rendering parameter settings given the data; and (3) A method for determining the unknown control mapping function C from sensor data to rendering parameters.

This problem is highly analogous to that encountered in haptic texture rendering for manual interaction, for which several researchers have developed approaches to sampling material features from real-world surfaces [8, 1], inspired by similar practices in computer graphics and imaging.

Measurement procedure A measurement apparatus was designed to record the interactive response of ground materials to the walker. A hard-soled men's dress shoe (Figure 3) was instrumented with six force sensing resistors (Interlink model 402), 3 in the toe and 3 in the heel region, two acoustic vibration transducers (AKG model C-411 PP) respectively attached to the toe and heel region of the shoe, and a nearby acoustic microphone (Neumann KM 183) unattached to the shoe. An accelerometer was attached to the mid-sole region of the shoe for a subset of the recordings.

Temporal profiles of the interaction were recorded as a subject walked on twelve different materials. Examples are given by the first two subplots of figure 4. The materials included six aggregates (different sizes of stone, gravel, and sand) and six solid surfaces (wood, vinyl, ceramic, marble, rubber, and carpet). The force sensing resistor data was subsequently calibrated using a laboratory scale, providing force data with an accuracy of approximately +/- 10 Newtons respectively for toe and heel. A similar calibration has been performed with the sensors of the tile itself.

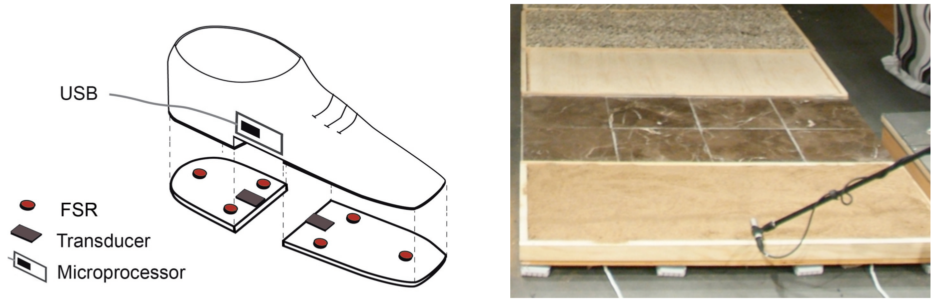

Fig. 3. The measurement apparatus and material samples.

2.2 Model parameter identification: Aggregates

The identification of synthesis model parameters from this data is ongoing work, but we describe it briefly here. For aggregate interactions, the most salient parameters are the modal frequencies and decay times of the material and the force-to-impact event rate correspondence. The same procedure can be used for either vibrational or acoustic data. Modal resonances are extracted from the data by linear predictive coding, from periods containing few, isolated impacts.

A relation between the (stochastic) impact event rate $N(t)$ and the differential force input $v_F(t)$ can be inferred from the recordings. We have extended the PhISEM analysis method presented by Cook [2] for this purpose. Briefly, the vibration channel $y(t)$ of a material data recording is analyzed using a Debauchies wavelet decomposition. The second detail coefficient $d_2(t)$, representing the 6-12 kHz band (which isolates well the impact onsets) is identified. A continuous crumpling measure $I(t)$ is extracted from the rectified subband signal using an L_2 norm on a sliding window: $I(t) = \left[g(t) * (d_2(t)^2)\right]^{1/2}$ Here, $*$ is convolution, and $g(t)$ is a Gaussian window function. Based on the ansatz of Cook, the event rate $N(t)$ is assumed to be of the form $N(t) = e^{\alpha I(t)} - 1$. The parameter α is an unknown value (constant for all materials), that allows to tune the relative significance of more and less event-dense regions.

Figure 4 shows representative results for a single footstep measurement taken on gravel. The differential force input profile $v_F(t)$ bears a qualitative resemblance to the estimated impact event rate profile $N(t)$. Consequently, in the interactive device, the sensed differential force exerted on the tile is used as an input to the synthesis model, linearly controlling the event rate, and (indirectly) to the energy level of impacts. Our current work aims to determine a better control law from applied force to impact process parameters for various materials.

3 Conclusions

The haptic interactive device presented here raises questions as to the nature and distinctive features of haptic interaction between the foot and ground surfaces.

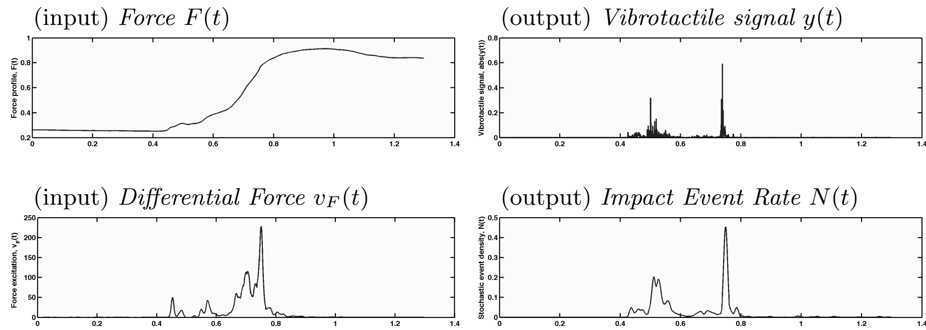

Fig. 4. *Left panels (top and bottom)*: (input) force signals $F(t)$ and $v_F(t)$ for a subject stepping onto gravel. *Right panels*: Measured (output) signals, the rectified vibrotactile response profile $y(t)$ of the material (top) and the estimated event rate $N(t)$.

Some of these questions are novel compared to those that have arisen in the context of manual haptic interaction, as exemplified by the aggregate material simulation described here. As noted, such vibrotactile interaction methods may also be viewed as complementary to those that have been addressed by prior research on virtual haptic locomotion interfaces.

While the design methodology described here is still being developed, it is an attempt to define a measurement-based approach to shaping the interactive behavior of the device to match that of a ground material of interest. The data-driven model parameter identification problem can be applied, in principle, to any effective model of the physics involved. A general engineering solution to this problem, applicable to arbitrary ground material interactions, remains to be defined.

Acknowledgments. The McGill authors gratefully acknowledge the Natural Sciences and Engineering Research Council of Canada and the Centre for Interdisciplinary Research in Music Media and Technology. Further support is provided by the EU project CLOSED, FP6-NEST-29085.

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