Interaction Capture in Immersive Virtual Environments via an Intelligent Floor Surface

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ABSTRACT

We present techniques to enable users to interact on foot with simulated natural ground surfaces in immersive virtual environments. Position and force estimates from in-floor force sensors are used to enable interaction with deformable ground surfaces, such as soil or ice, presented in a virtual environment and accompanied by plausible auditory, and vibrotactile feedback.

1 INTRODUCTION

Sensations accompanying walking on natural ground surfaces in real world environments (sand in the desert, or snow in winter) are multimodal and highly evocative of the settings in which they occur [8]. Limited prior research has addressed foot-based interaction with VR and AR environments. Arguably, one reason has been the lack of efficient techniques for capturing foot-floor contact interactions via distributed floor areas. Here, we present a novel solution using a network of instrumented floor tiles, and methods for capturing foot-floor contact interactions so as to render multimodal responses of virtual ground materials.

Devices for enabling omnidirectional in-place locomotion in VEs exist [2], but are complex and costly. Most prior work on tactile interaction with floor surfaces utilizes surface sensing arrays (e.g., [4, 6]) for applications such as person tracking, activity tracking, or musical performance. Commercial entities such as Gesturetek and Reactrix have developed floor interfaces for dynamic visual displays of liquid or solid objects. In such cases, video sensing is often used, but it provides no direct information about contact forces. Such information is needed for simulating highly contact-dependent interactions with virtual materials. For further references, see [9].

2 DISTRIBUTED FLOOR INTERFACE

The floor interface consists of a 6×6 array of rigid tiles covering a 3.5 sq. m area. Each tile is instrumented with four force sensors and a vibrotactile (VT) actuator. The floor is coated in projection paint, and a pair of overhead video projectors is used for visual display. The design of the actuated tile interface is described in detail elsewhere [7, 9]. It consists of a rigid plate $30.5 \times 30.5 \times 2$ cm in size, supported on vibration mounts, and coupled to a voice coil actuator. Actuators are driven by audio signals that are generated by a computer and amplified. The device has a passband from about 50 Hz to 750 Hz, and can reproduce the largest forces required for interaction with virtual ground surfaces (i.e., more than 30 N across the passband). We sense normal forces below the vibration mounts using resistive force sensors (Interlink model 402 FSR). This data is conditioned, amplified, and digitized via a 32-channel, 16-bit acquisition board, and relayed over Ethernet. An array of 6 small form factor computers is used for force data processing and audio-vibrotactile (VT) synthesis. Each is responsible for synthesizing VT feedback from 6 tiles, ensuring a palpable response to force input can be provided at low latencies. Data is forwarded to a separate visual rendering server.

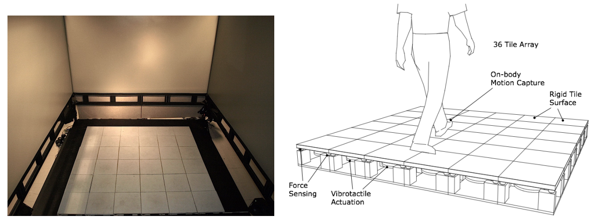

Figure 1: Left: Distributed floor interface situated within an immersive, rear projected VE simulator. Right: illustration showing sensing and actuating components.

3 INTRINSIC CONTACT SENSING

Intrinsic contact sensing resolves locations and forces of surface contact between objects using internal force and torque measurements [1]. It can provide high resolution estimates of contact position with fewer sensors than are needed for surface-based sensing. It has mainly been applied to problems in robotic manipulation, but we have adapted it to foot-ground interaction sensing [9]. The method is based on resolving the contact centroid $\mathbf{x}_c$ associated with a pressure distribution $p_R(\mathbf{x})$. $\mathbf{x}_c$ is a unique point on the floor such that there is a normal force F_c that gives rise to the same intrinsic force measurements as $p_R(\mathbf{x})$ does [1]. It provides a concise summary of the foot-floor contact locus, but does not indicate shape or orientation. The sensing problem is simple to formulate for a single floor tile (Fig. 2), with force sensor locations $\mathbf{x}_j$ where internal force measurements f_j are taken and j indexes the tile sensors. The contact centroid $\mathbf{x}_c$ and normal force $\mathbf{F}_c = (0,0,F_c)$ can be recovered from scalar force measurements $\mathbf{F}_j = (0,0,f_j)$ via force and torque equilibrium equations,

$$\begin{aligned} \sum_{j=1}^{4} f_j + F_c + f_p &= 0 \\ \sum_{j=1}^{4} \mathbf{x}_j \times \mathbf{F}_j + \mathbf{x}_c \times \mathbf{F}_c + \mathbf{x}_p \times \mathbf{F}_p &= 0. \end{aligned} \quad (1)$$

$\mathbf{F}_p = (0,0,f_p)$ is the weight of the the plate and actuator at the tile's center $\mathbf{x}_p$. The three nontrivial scalar equalities (1) can be solved for the contact centroid parameters, yielding:

$$F_c = \sum_{i=1}^{4} f_i - f_p, \quad \mathbf{x}_c = \frac{1}{F_c}\left(\sum_{i=1}^{4} (\mathbf{x}_i - \mathbf{x}_p) f_i + f_c \mathbf{x}_p\right) \quad (2)$$

This result can be readily extended to cases in which $p_R(\mathbf{x})$ overlaps several tiles [9].

Through measurements we determined that contacts can be localized with a typical accuracy of 1.5 cm, and a worst-case value of 4 cm. These numbers compare favorably to the linear dimensions of the tile (30 cm) and the typical width of an adult shoe. Further details are given in [9].

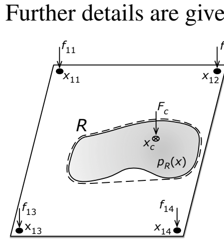

Figure 2: Contact centroid $\mathbf{x}_c$ from pressure distribution $p_R(\mathbf{x})$.

Figure 3: Still image from the frozen pond scenario.

3.1 Channeling interaction with virtual materials

As a demonstration, we implemented a virtual frozen pond that users may walk on. As they do, patterns of cracks form in the surface ice, depending on locations and forces of foot-floor contact (Fig. 3), and rendered via audio, visual, and VT channels. This is a setting that can be rendered independent of foot-floor contact shape, unlike deformable soils or snow, where foot pressure distribution is required [8].

3.1.1 Audio-tactile rendering

Audio and VT display channels provide feedback accompanying the fracture of the virtual ice sheet underfoot. The two are derived from a simple, physically motivated stochastic process [8] (Fig. 4), modeling fracture events via an event time t_i and energy loss E_i. Independent responses are rendered in parallel for each tile. The elastic part of the stress-strain relationship is modeled as: $f(t) = m\ddot{x} + b\dot{x} + Kx$, where f is the net foot-floor force on the tile, x is a virtual displacement, and m, b, and K are parameters governing the density, viscous damping and stiffness of the local ice mass. The distribution of fracture event time intervals is modeled via a Poisson process $p(t) = \lambda \exp(-\lambda t)$ whose rate is the one-sided energy: $\lambda \equiv \kappa_+(t) = \frac{1}{2}m\dot{x}^2$, where $\kappa_+ = 0$ if $\dot{x} < 0$ ensures that fracture occurs with increasing load. The energy $E(t)$ of a fracture event at time t is sampled from an exponential distribution $p(E) \propto E^\gamma$ with material-related scale parameter γ [8]. The audio and VT signatures accompanying such an event are synthesized as discrete impulses with energy E passed through a simple representation of the resonant response of the surface. The latter is synthesized via a bank of modal oscillators with impulse response $s(t) = \sum_i a_i e^{-b_i t} \sin(2\pi f_i t)$, determined by amplitudes a_i, decay rates b_i, and frequencies f_i.

3.1.2 Visual animation and control

Approaches to the animation of surface cracks are often based on simulating the inelastic evolution of the stress distribution [5, 3]. We adopt a simplified approach, modeling stress release via the stochastic process described above. This preserves timing correlation between modalities, and ensures that perceptually harder temporal requirements of the audio-VT channels can be met. The contact centroid $\mathbf{x}_c$ provides an efficient summary of the spatial stress injected by the foot. A fracture pattern consists of a collection of crack fronts, defined by linear sequences of node positions, $\mathbf{c}_0, \mathbf{c}_1, \ldots, \mathbf{c}_n$. Fronts originate at seed locations $\mathbf{p}$, such that $\mathbf{p} = \mathbf{c}_0$. The fracture is rendered as line primitives $\ell_k = (\mathbf{c}_k - \mathbf{c}_{k-1})$ on the ice sheet (Fig. 4). Seed locations $\mathbf{p}$ are determined by foot-floor contact. Our method is mesh-free, and the seed locations are unconstrained. A crack event initiated by the audio-tactile process at time t_i with energy $E(t_i)$ results in the creation of a new seed or the growth of fractures from an existing one. A new seed $\mathbf{p}$ is formed at the location of the dominant contact centroid $\mathbf{x}_c$ if no existing seed lies within distance Δp. The new seed $\mathbf{p}$ is created with a random number N_c of latent crack fronts, $\mathbf{c}_0^1, \mathbf{c}_0^2, \ldots \mathbf{c}_0^{N_c}$. We sample N_c uniformly in $2, 3, \ldots 6$. A crack front propagates from a seed $\mathbf{p}$ nearest to $\mathbf{x}_c$. With probability $1/N_c$ the jth crack front of $\mathbf{p}$ is extended. Its growth is determined by a

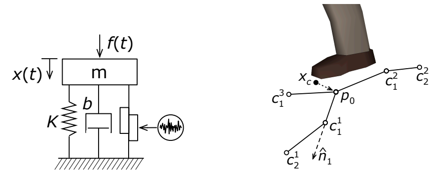

Figure 4: Left: Crack process at a tile, modeled via elements with stiffness k, mass m, damping b, and stochastic slip unit. Right: Crack patterns are graphs of lines between nodes $\mathbf{c}_i$.

propagation vector $\mathbf{d}_m^j$ such that $\mathbf{c}_m^j = \mathbf{c}_{m-1}^j + \mathbf{d}_m^j$. We take $\mathbf{d}_m^j = \alpha E \hat{\mathbf{n}}_m^j$, where E is the crack energy, α is a global growth rate parameter, and $\hat{\mathbf{n}}_m^j$ is the direction. Since we lack information about the principal stress directions at the front, we propagate in a direction $\hat{\mathbf{n}}_m^j = \hat{\mathbf{n}}_{m-1}^j + \beta \hat{\mathbf{t}}$, where $\beta \sim N(\beta; 0, \sigma)$ is a Gaussian random variable and $\hat{\mathbf{t}} = \hat{\mathbf{n}}^j \times \hat{\mathbf{u}}$, where $\mathbf{u}$ is the upward surface normal (i.e., $\mathbf{t}$ is a unit vector tangent to $\hat{\mathbf{n}}^j$). The initial directions at $\mathbf{p}$ are spaced equally on the circle.

4 Conclusion

This paper described techniques for interaction with virtual ground material simulations using a distributed, multimodal floor interface. The methods are low in cost and complexity, and accessible to multiple users without body-worn markers or equipment. Despite these promising results, there are several aspects in which this system can be improved, including: tile sensing accuracy, tile array density, the use of multi-tile force data, and more accurate physical simulation of ground materials. Nonetheless, we believe that these methods hold promise for improving presence in immersive VR and AR environments.

Acknowledgements

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