Contact Sensing and Interaction Techniques for a Distributed, Multimodal Floor Display

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ABSTRACT

This paper presents a novel interface and set of techniques enabling users to interact via the feet with augmented floor surfaces. The interface consists of an array of instrumented floor tiles distributed over an area of several square meters. Intrinsic force sensing is used to capture foot-floor contact at resolutions as fine as 1 cm. These sensing techniques are combined with multimodal display channels in order to enable users to interact with floor-based touch surface interfaces. We present the results of a preliminary evaluation of the usability of such a display.

1 INTRODUCTION

Foot operated interfaces have long been used to aid work in complex, manually intensive environments, ranging from dental offices to textile factories. However, comparatively little research has addressed foot-based interaction with the computational world. Such interactions could be beneficial to fields that require hands free control, such as medicine. Arguably, one factor that has limited the use of foot-based interaction for computationally augmented environments is the lack of efficient interfaces and interaction techniques capable of capturing touch via the feet over a distributed display. In this paper, we present the design of an interface based on a distributed network of low-cost, rigid floor tile components, with integrated sensing and actuation capabilities. In order to make good use of this system, we draw on contact based sensing techniques that are able to capture foot-floor interactions with much finer resolution than is achieved if the tile is regarded as the smallest relevant spatial unit.

1.1 Foot Input in Human-Computer Interaction

Examples of the use of foot-controlled input in HCI, interactive arts and video gaming date at least as early as Amiga's Joypad (1983) [12]. Pearson and Weiser later introduced a foot input device for a desktop PC [9]. Despite the sustained interest in touch screens for the hands, less research has addressed the design and usability of similar interfaces for the feet. Companies such as Gesturetek and Reactrix have developed interactive floor-based visual displays using video sensing technology, but such sensors provide no direct information about foot-floor contact forces and positions. Such information is arguably essential for rendering interactions with virtual objects or controls. Moreover, the potential for floor-based multimodal (visual, auditory, tactile) information displays has only recently begun to be addressed [13].

In the domain of immersive virtual environments (VEs), devices for enabling omnidirectional in-place locomotion in VEs exist [**?**], but are complex and costly. Lower cost methods for navigation and interaction in VEs, such as the shoe-based Step WIM interface of LaViola et al. [6], require special apparel and provide limited feedback. Most prior work on tactile interaction with floor surfaces utilizes surface sensing arrays (e.g., [8, 11]) for applications such as person tracking, activity tracking, or musical performance. Although similar sensing interfaces are now commercially available, costs remain high. Further comparison with tactile sensing methods is provided in Sec. 3.

2 SYSTEM DESCRIPTION AND COMPONENTS

The floor interface (Fig. 1) consists of a square array of 36 rigid tiles, each of which is instrumented with force sensors (four per tile) and a vibrotactile (VT) actuator. The floor is coated in gray projection paint. A pair of overhead video projectors is used for visual display, in order to reduce the impact of shadows cast by users. The tiles are rigid, composite plates with dimensions $30.5 \times 30.5 \times 2$ cm, supported by elastic vibration mounts, and coupled to a vibrotactile (VT) actuator (Clark Synthesis, model TST229) beneath the plate. Actuator signals are generated on personal computers, output via digital audio interfaces, and amplified. The actuator signals are generated on a personal computer. The floor tile display achieves a VT passband from about 50 Hz to 750 Hz, and is capable of reproducing the largest forces needed for interaction with virtual ground surface objects or properties (i.e., more than 30 N across the indicated frequency band).

Normal forces are sensed at locations below the corner vibration supports of each tile using a total of four resistive force sensors (Interlink model 402 FSR). Analog data from the force sensors is conditioned, amplified, and digitized via a 32-channel, 16-bit data acquisition board. Each sensor is sampled at a rate of up to 1 kHz transmitted over a low-latency Ethernet link. An array of 6 small form factor computers is used for force data processing and audio-VT rendering. A separate server on the same data network is responsible for rendering visual feedback and managing user input.

3 INTRINSIC CONTACT SENSING

Intrinsic contact based sensing aims to resolve the locations of soft-body contact, forces at the interface, and the moment about the contact normals using internal force and torque measurements [2]. It is assumed to involve contact between a rigid apparatus and an object (here, a foot) in the environment. It has mainly been applied to problems in robotic manipulation, but we have adapted it to foot-ground interaction sensing. This approach can be viewed as an alternative to sensing foot-floor contact via dense surface mounted transducer arrays, relative to which far fewer sensors are required. The method is based on resolving the contact centroid $\mathbf{x}_c$ associated with a pressure distribution $p_R(\mathbf{x})$ distributed over an area R. $\mathbf{x}_c$ 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 [2]. 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,

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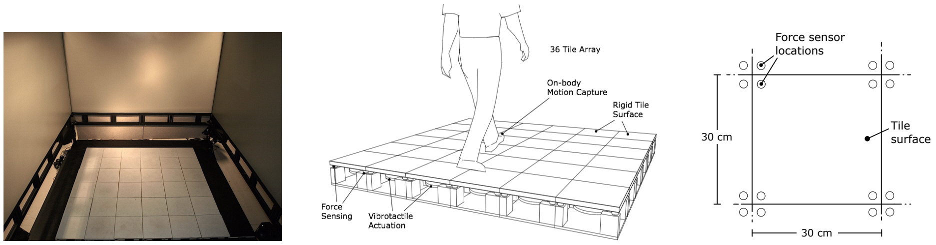

Figure 1: Left: The floor interface is situated within an immersive, rear projected virtual environment simulator. Middle: Sensing and actuating components are integrated beneath the floor. Right: View from above showing sensor locations.

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

$\mathbf{F}_p = (0,0,f_p)$ 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:

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

The contact centroid lies within the convex hull of the contact area (dashed line, Fig. 2) at the centroid of the pressure distribution [2]. It thus provides a concise summary of the foot-floor contact locus, but does not provide information about shape or orientation. When the foot-floor contact area overlaps two or more tiles, the pressure centroid $\mathbf{x}_R$ for the entire contact area can be computed from contact centroids $\mathbf{x}_{ck}$ for each tile (computed from Eq. (2)). It is given by the weighted average $\mathbf{x}_c = w_1\mathbf{x}_{c1} + w_2\mathbf{x}_{c2}$, where $w_k = F_i/F$. The domain-independence of this result makes it possible to track these points as they move across tile boundaries.

Figure 3 shows a comparison of measured and estimated contact positions using the contact centroid method of Eq. (2). The data was acquired from a single calibrated floor tile. Despite distortion near tile edges, 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.

4 APPLICATIONS: FLOOR TOUCH UIS

We have applied these sensing methods to the implementation of virtual floor-based touch interfaces. In one set of examples, these consist of an array of standard user interface widgets that can be controlled with the feet (Fig. 4). Input is captured using the force sensing array, using a multi-touch screen metaphor mediated by a set of interaction points (cursor locations), which are defined as the contact centroids $\mathbf{x}_c$ with the largest forces. Force thresholds associated to a control are used to determine selection. The controls provide positive tactile feedback supplied by the actuators, in the form of synthesized click-like transient vibrations or sliding (friction) vibrations.

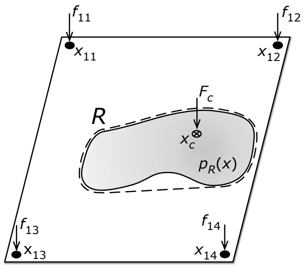

Figure 2: A normal force distribution $p_R(\mathbf{x})$ and associated contact centroid position $\mathbf{x}_c$.

Interface design toolkit Interface design is facilitated by a software layer and network protocol that abstracts the hardware systems (which are accessed over a local Ethernet network) and connects them to the user interface. This software layer processes the sensor data to extract interaction points, and provides them with IDs that persist throughout contact. Second, it allows to remotely cue and present VT feedback localized to the area defined by each interface object on the floor. The protocol design is based in part on the TUIO protocol for table-top touch interfaces [5].

4.0.1 Preliminary User Evaluation

A question we soon encountered when beginning to design such touch-surface applications concerned the appropriate size of virtual controls. The answer can be presumed to depend on factors including sensing limitations, users' motor abilities, target parameters, and feedback modality or modalities; such usability factors have been extensively studied and modeled in the HCI literature [7, 4]. The spatial scale appropriate for touch screen controls has been shown depend on the interaction technique adopted. For example, precision control strategies can enable single pixel accuracy in finger-based touch screen interaction [1, 10], and related techniques may prove effective for use with a foot-operated touch screen interface. Limited research has addressed floor interfaces (Sec. 4), so we focused here on a basic task requiring the selection of controls presented at various locations and sizes to a stationary user.

Human movement research has investigated foot movement control in diverse settings. Visually guided targeting with the foot has been found be effectively modeled by a similar version of Fitts' law as is employed for modeling hand movements, with an execution time about twice as long for a similar hand movement [3]. However, the present, preliminary, investigation addresses a situation in which usability is manifestly co-determined by both operator and device limitations, providing a window on both.

Apparatus The apparatus is the floor interface presented above. Although the sensor calibration used for this experiment was less accurate by a factor of two than that which yielded the position estimates noted above, it is sufficient for interaction points to be effectively tracked over extended distances on the floor, as shown in the video.

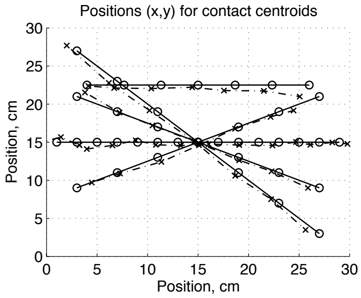

Figure 3: Measurements comparing true normal force positions (circles) with contact centroid estimates (Xs).

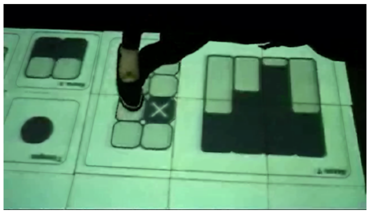

Figure 4: Still image from video of a user interacting with floor-based interface widgets.

Stimuli and method The stimuli consist of round virtual buttons to be selected by users, who began each trial with their feet in locations marked by white rectangles. Users could activate a button by pressing it in a way that resulted in a contact centroid within the area of the button exceeding a force threshold of about 35 N. The buttons ranged in diameter from 4.5 to 16.5 cm, and were presented at four distances, on lines radiating from between their feet, oriented at one of two angles relative to the horizontal, as shown in Fig. 5. Upon selection, the buttons provided visual feedback in the form of a 20 cm white disc centered in place of the original appearance. All buttons provided the same feedback. Only the buttons and foot locations were visible. No audio or VT feedback was provided.

Hypothesis We expected users' mean successful selection rate to follow a monotonic curve that increases with target size and decreases with target distance. Interaction between target distance and width may be anticipated here, but we do not attempt to validate a model. We expected a moderately high success rate to be achieved for targets that are at least as wide as the foot.

Participants Eight participants, ranging in age between 21 and 38, kindly volunteered for this study. All of them were research staff or students in the Faculty of Engineering.

Procedure Participants wore their own shoes during the experiment, and selected targets with their preferred, dominant foot. Participants were instructed to activate the buttons precisely and quickly. The non-preferred foot was not constrained, but participants were required to return both feet to the two rectangular regions shown in Fig. 5 between stimuli. Most chose to leave their non-preferred foot in place throughout each session.

The experiment began with a practice period lasting 3 minutes, followed by the main experiment. The latter consisted of two sessions of 12 minutes, with a short pause between. A total of 240 stimuli were presented to each participant. Stimuli were presented in sequential, randomized order. Each button appeared and remained visible and active for two seconds during which users were able to select it. A three second pause followed, after which the next button appeared. The success of selection, and time required, were recorded. Participants completed a response questionnaire and provided comments verbally afterward.

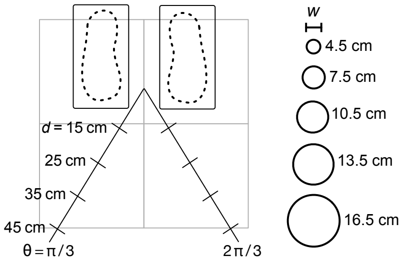

Figure 5: Configuration and stimuli from the experiment.

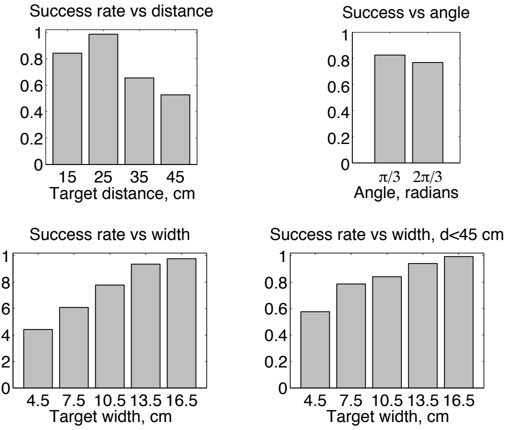

Figure 6: Top Left: Successful target selection rate vs. distance, averaged across the other conditions. Top Right: Success rate vs. angle of presentation (measured away from preferred foot). Lower Left: Successful target selection rate vs. button width, averaged across the other conditions. Lower Right: The same measure, excluding the farthest targets.

Analysis Summaries of the success frequencies are presented in Figures 6 and **??**. Using a logistic regression analysis, we determined that the main factors of width w, distance d, and bearing angle θ significantly affected success of selection ($p < 0.001$). The fitted logit is $z = 1.4 + 0.071w - 0.062d - 0.6\theta$ (with t-values > 7.8). θ is in radians, increasing away from the preferred foot; d and w are measured in cm. The model correctly predicts 86% of the responses.

Discussion Users selected larger targets within the allotted two-second interval at a higher rate of success than smaller ones. Performance with the largest was very high (98%), and that for the smallest was low (44%). Small targets pose two potential problems. First, they can be occluded by the foot during selection. This problem appeared to be mitigated because targets could be seen before selection, while during selection they were projected on the top of the foot. Second, limitations on precise control can arise from factors such as: shoe width, human motor abilities, and sensor positioning errors. Six out of eight participants reported finding a strategy to activate the smallest buttons, by using a feature of the shoe or changing the applied force. Conversely, software interaction techniques for improving precise control are known in the literature on touch screen displays [1, 10], and we intend to investigate these in future work. Nearby targets, at distances of 15 to 25 cm, were selected at a higher rate. However, performance was better at 25 cm than at the nearest distance of 15 cm (98.5% vs. 84%, with $p < 0.001$ using Fisher's exact test, 2-tailed). One possible explanation is that if an interface element is beneath a standing user, it can be occluded from view by the body, or present a difficult viewing angle. Although a mobile user may be able to avoid such "dead zones", they may be an important design consideration. The discussion is also complicated by the fact that, for our device, position sensing is most accurate near the centers of the tiles, as indicated in the preceding section. This was noticed by users of the system, two of whom volunteered that they had learned to better activate small buttons that were close to edges by pressing them off-center. The design of improved algorithms for compensating positioning distortions is being addressed in our ongoing work.

Participants consistently reported difficulty in selecting targets that were on the line oriented away from their active, selecting foot. However, bearing angle appeared to have a minor, if significant, effect on performance (Fig. **??**). It is possible that these responses were more indicative of a larger motor effort than an inability to perform the selection. Neck fatigue was most frequently cited by participants as a source of discomfort.

Future work Although these results are suggestive, further work is needed in order to characterize the usability aspects of this display, and others like it. A greater understanding of factors such as control element size, display scale, motor abilities, modalities, and other aspects salient to the use of such a device will certainly be needed.

One notable question not addressed by this study concerns the interplay between users' movements on foot and their interactions with the touch surface. A novel aspect is that, implicitly, both feet are involved, due to requirements of movement and of maintaining balance. In everyday actions, like striking a soccer ball, weight is often shifted onto one foot, which specifies an anchored location, while the opposite is used to perform an action. Floor interfaces that involve movement may thus be expected to have something of the flavor of bimanual interaction in HCI, a connection we intend to explore in future work.

4.0.2 Floor UIs: Potential application space

Floor controls are common in many areas of man-machine interaction in which the hands are occupied, such as manufacturing, mass transportation, surgery, or dentistry. Virtual foot control surfaces could have advantages in such domains. The software virtualization of user interfaces provides numerous advantages that are familiar in HCI. Specific to the feet, certain applications areas, such as those related to pedestrian navigation or map-based visualization, may emerge as particularly salient. In domains such as medicine, ergonomic problems with existing foot controls have been documented in prior literature [14]. Other domains of relevance, including entertainment, gaming, and marketing, were mentioned in the introduction.

5 CONCLUSIONS

This paper presented interaction techniques based on intrinsic contact based force sensing via a novel distributed floor interface. Such an approach may well-suited to situations in which foot-floor contact interactions are of particular interest. Such information is not usually available through other optical sensing channels, such as motion capture. The system is low in cost and complexity, and the methods presented can be employed by multiple simultaneous users, without any specialized apparel. In addition, this paper demonstrates the integration of these interaction techniques within multimodal displays implementing virtual ground surface simulations or floor-based control interfaces. Despite the promising nature of these results, there are several respects in which the present system might be improved or extended:

- Our system senses 3 DOF per tile, equivalent to the normal force f_c and position $\mathbf{x}_c$ of the contact centroid. To solve this sensing problem required assuming frictionless soft contact (Sec. 3). A future interface capable of sensing the full 6 rigid DOF of the tiles via additional force sensors, would achieve greater accuracy by accounting for friction effects.
- A floor interface with a denser array of tiles would be capable of capturing more information about foot-ground contact shape.
- During multi-tile foot-floor contact, a contact-based sensing approach results in clusters of contact centroids. New techniques are needed in order to acquire the information arising from such features.
- Our methods are able to follow moving interaction points only as long as foot-floor contact is sustained, while in some applications, one may wish to know if the same foot is used for separate acts of selection. We are addressing this issue within a Bayesian filter tracking paradigm.
- As noted more extensively in Sec. 4.0.1, above, further work is needed in many areas of usability in order to develop design guidelines and strategies for floor-based interfaces.

It is hoped that the present contribution convinces the reader of the potential of such floor-based interaction methods, and that other researchers are inspired to contribute in areas such as those noted above, or in others that have not yet been anticipated.

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