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

Yon Visell, Severin Smith, Alvin Law, Rishi Rajalingham, Jeremy R. Cooperstock
McGill University, Montreal, Canada

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, for use with floor-based multimodal touch surface interfaces. We present the results of a preliminary evaluation of the usability of such a display.

Keywords: Foot interaction, Multimodal display

1 INTRODUCTION

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 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.

2 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) [13]. Pearson and Weiser later introduced a foot input device for a desktop PC [10]. 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. Floor-based multimodal (visual, auditory, tactile) information displays have only recently begun to be investigated [14]. In the domain of immersive virtual environments (VEs), devices for enabling omnidirectional in-place locomotion in VEs exist [4], 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. [7], require special apparel and provide limited feedback. Most prior work on tactile interaction with floor surfaces utilizes surface sensing arrays [9, 12], for applications such as person tracking, activity tracking, or musical performance. Although similar sensing interfaces are now commercially available, costs remain high. Further differences between tactile sensing and our approach are noted in Sec. 4.

3 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 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 floor tile display achieves a VT passband from 50 Hz to 750 Hz, and is capable of reproducing the largest forces needed for interaction with virtual ground surface objects or properties (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 six small form factor computers is used for force data processing and audio-VT rendering. A separate, networked server is responsible for rendering visual feedback and managing user input.

4 INTRINSIC CONTACT SENSING

Intrinsic contact based sensing aims to resolve the locations of contact, the 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). This approach has mainly been applied to problems in robotic manipulation, but we have adapted it to foot-ground interaction sensing. It can be viewed as an efficient alternative to sensing via dense surface mounted arrays, as it requires far fewer sensors. The method resolves the contact centroid $\mathbf{x}_c$ associated with a pressure distribution $p_R(\mathbf{x})$ that is distributed over an area R. $\mathbf{x}_c$ is a contact point such that a point 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. We ignore friction effects for the moment. 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,

$$\sum_{j=1}^{4} f_j + F_c + f_p = 0 \quad (1)$$

$$\sum_{j=1}^{4} \mathbf{x}_j \times \mathbf{F}_j + \mathbf{x}_c \times \mathbf{F}_c + \mathbf{x}_p \times \mathbf{F}_p = 0. \quad (2)$$

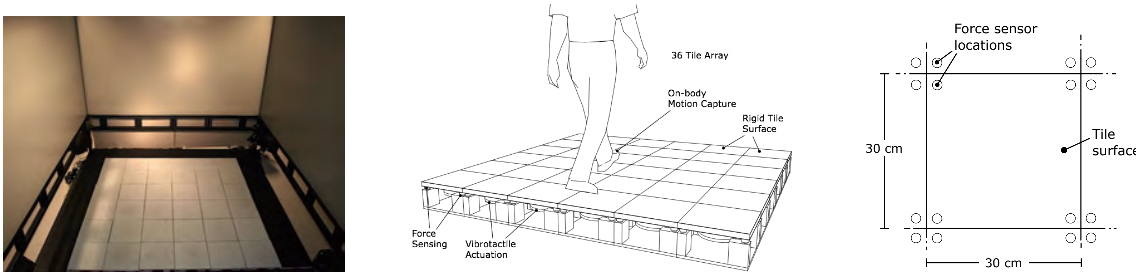

Figure 1: Left: The floor interface is situated within an immersive, rear projected virtual environment simulator. Middle: Sensing and actuating components are integrated beneath the floor. Right: View from above showing sensor locations.

$\mathbf{F}_p = (0,0,f_p)$ is the weight of the the plate and actuator at the tile's center $\mathbf{x}_p$. The three nontrivial scalar equalities (1, 2) can be solved for contact centroid parameters:

$$F_c = \sum_{i=1}^{4} f_i - f_p, \quad \mathbf{x}_c = \frac{1}{F_c}\left(\sum_{i=1}^{4}(\mathbf{x}_i - \mathbf{x}_p)f_i + f_c\mathbf{x}_p\right) \qquad (3)$$

The contact centroid lies within the convex hull of the contact area (dashed line, Fig. 2) at the centroid of the pressure distribution [2], and thus provides a concise summary of the foot-floor contact locus, but not 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. (3)). 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 thus makes it possible to track these points as they move across tile boundaries. Figure 3 represents results of real measurements of 50 estimated contact positions determined by the method of Eq. (3), using a single calibrated floor tile. Despite distortion near tile edges, contacts were localized with a typical accuracy of 1.5 cm, and worst-case values of ≈ 3 cm, smaller than the linear dimensions of the tile (30 cm) or the typical width of a shoe.

5 Applications: Floor Touch UIs

These sensing methods can be employed to implement virtual floor-based touch interfaces. One set of examples we have created consist of array of standard UI widgets to be controlled with the feet (Fig. 4). Input is based on 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 with 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.

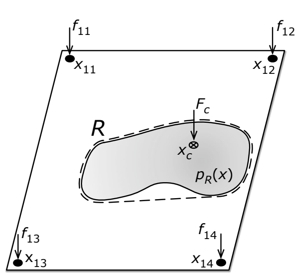

Figure 2: A normal force distribution $p_R(\mathbf{x})$ and associated contact centroid position $\mathbf{x}_c$.

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 [6].

5.1 Preliminary User Evaluation

A question we encountered when beginning to design such touch-surface applications concerned the appropriate size of virtual controls. The required size depends on factors including sensing limitations, users' motor abilities, target parameters, and feedback modalities, as has been extensively studied and modeled in the HCI literature [8, 5]. The size appropriate for touch screen controls has been shown to depend on the interaction technique adopted. Precision control strategies can enable single pixel accuracy in finger-based touch screen interaction [1, 11], and related techniques may prove effective for use with the feet. Limited research has addressed floor interfaces (Sec. 5), 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 to 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. Due to the floor size, the sensor calibration was less accurate by a factor of two than that which yielded the position estimates noted above, but was sufficient for interaction points to be

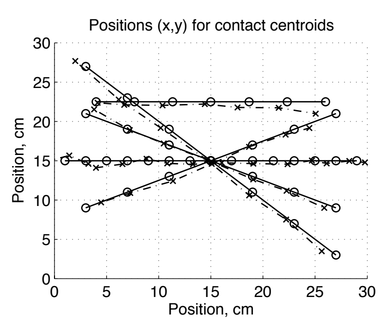

Figure 3: Results of 50 measurements comparing true normal force positions (circles) with contact centroid estimates (Xs).

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

effectively tracked over extended distances on the floor, as shown in the supplementary video.

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, 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 displayed. No audio or VT feedback was provided.

Hypothesis We expected user performance to improve with target size and degrade with target distance. Interaction between target distance and width might be anticipated, but we do not attempt to validate a model. We expected good performance for targets that are at least as wide as the foot.

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

Procedure Participants wore their own shoes during the experiment, and selected targets with their preferred, dominant foot. They 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 three minutes, followed by the main experiment. The latter consisted of two sessions of 12 minutes, with a short pause in 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 verbal comments afterward.

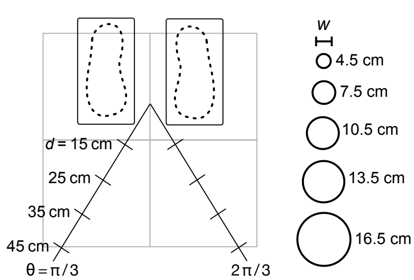

Figure 5: Configuration and stimuli from the experiment.

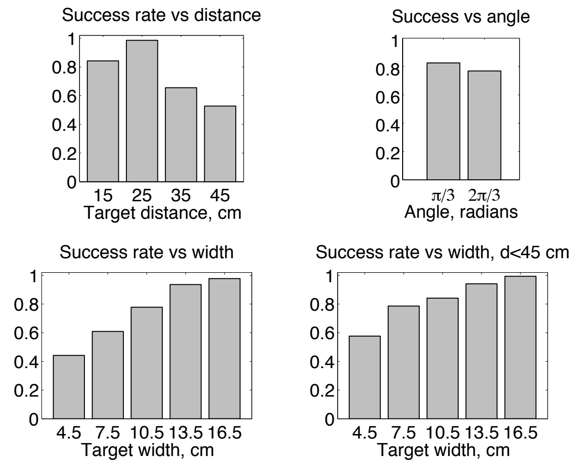

Figure 6: Top Left: Successful target selection rate vs. distance, averaged across the other conditions. Top Right: Success rate vs. angle of presentation (measured away from preferred foot). Lower Left: Successful target selection rate vs. button width, averaged across the other conditions. Lower Right: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

Analysis Summaries of the success frequencies are presented in Figure 6. 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, as with other touch surface displays, targets 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 small buttons by using a feature of the shoe or changing the applied force. Software interaction techniques for improving precise touch screen control are known [1, 11], and we intend to investigate these in future work. Nearby targets (distances of $D = 15$ 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, two-tailed). One likely reason 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. Due to such effects we would not expect selection time T to follow a Fitts' Law relation, $T = a + b\log_2(D/W)$, but this was not tested here. Although a mobile user may be able to avoid visibility problems, they seem to be an important consideration. 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. In ongoing work, we are developing algorithms for correcting such positioning distortions. Participants consistently reported difficulty in selecting targets that were oriented away from their active, selecting foot, however the effect of bearing angle on performance was small (Fig. 6). It is possible that these responses were indicative of a larger motor effort. 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.

5.2 Floor UIs: Potential application space

Virtual floor controls could be advantageous in some areas of man-machine interaction in which foot interfaces are common, such as manufacturing, mass transportation, or dentistry. Certain applications areas, such as those related to pedestrian navigation or map-based visualization, may emerge as particularly salient. In domains such as medicine, documented problems with existing foot controls might be overcome [15]. Other fields, including entertainment, gaming, and marketing, were noted in the introduction.

6 Conclusions

This paper presented interaction techniques based on intrinsic contact based force sensing via a novel distributed floor interface. Such foot-floor contact information is not usually available through optical sensing channels such as motion capture. The system is low in cost and complexity, and 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 three DOF per tile (the normal force f_c and position $\mathbf{x}_c$). To solve the sensing problem required assuming frictionless contact (Sec. 4). A future interface for sensing the full six rigid DOF per tile (via additional sensors) would remove this assumption.

– 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.

– Interaction points can be followed only as long as foot-floor contact is sustained. Methods for tracking users' feet between gestures or actions would be desirable.

– As noted more extensively in Sec. 5.1, above, further work is needed in many areas of usability in order to develop design guidelines and strategies for floor-based interfaces.

It is nonetheless hoped that this contribution succeeds in highlighting the potential of floor-based touch surfaces.

Acknowledgements

The authors acknowledge support from the MDEIE of Quebec for the EU FP7 project NIW (no. 222107).

References

[1] P. Albinsson and S. Zhai. High precision touch screen interaction. In *Proc of the ACM SIGCHI conference on Human factors in computing systems*, pages 105–112. ACM New York, NY, USA, 2003.

[2] A. Bicchi, J. Salisbury, and D. Brock. Contact sensing from force measurements. *The Int J of Robotics Research*, 12(3):249, 1993.

[3] E. Hoffmann. A comparison of hand and foot movement times. *Ergonomics*, 34(4):397, 1991.

[4] J. Hollerbach. Locomotion interfaces and rendering. *Haptic Rendering: Foundations, Algorithms and Applications. AK Peters, Ltd*, 2008.

[5] J. Jacko and A. Sears. *The human-computer interaction handbook: fundamentals, evolving technologies, and emerging applications*. Lawrence Erlbaum Assoc Inc, 2003.

[6] M. Kaltenbrunner, T. Bovermann, R. Bencina, and E. Costanza. Tuio: A protocol for table-top tangible user interfaces. In *Proc of Gesture Workshop 2005*. Gesture Workshop, 2005.

[7] J. LaViola Jr, D. Feliz, D. Keefe, and R. Zeleznik. Hands-free multi-scale navigation in virtual environments. In *Proc of the 2001 symposium on Interactive 3D graphics*, pages 9–15. ACM New York, NY, USA, 2001.

[8] I. MacKenzie. Fitts' law as a research and design tool in human-computer interaction. *Human-Computer Interaction*, 7(1):91–139, 1992.

[9] J. Paradiso, C. Abler, K.-y. Hsiao, and M. Reynolds. The magic carpet: physical sensing for immersive environments. In *CHI '97: CHI '97 extended abstracts on Human factors in computing systems*, pages 277–278, New York, NY, USA, 1997. ACM.

[10] G. Pearson and M. Weiser. Of moles and men: the design of foot controls for workstations. In *Proc of the ACM SIGCHI conf on Human factors in Comp Sys*, pages 333–339. ACM New York, NY, USA, 1986.

[11] R. L. Potter, L. J. Weldon, and B. Shneiderman. Improving the accuracy of touch screens: an experimental evaluation of three strategies. In *CHI '88: Proc of the SIGCHI conference on Human factors in computing systems*, pages 27–32, New York, NY, USA, 1988. ACM.

[12] A. Schmidt, M. Strohbach, K. v. Laerhoven, A. Friday, and H.-W. Gellersen. Context acquisition based on load sensing. In *UbiComp '02: Proc of the 4th international conference on Ubiquitous Computing*, pages 333–350, London, UK, 2002. Springer-Verlag.

[13] J. Sinclair, P. Hingston, and M. Masek. Considerations for the design of exergames. In *Proc of the 5th Int ACM Conf on Comp Graphics and Interactive Techniques, Southeast Asia*, page 295, 2007.

[14] Y. Visell, A. Law, and J. Cooperstock. Touch Is Everywhere: Floor Surfaces as Ambient Haptic Interfaces. *IEEE Transactions on Haptics*, 2009.

[15] L. Wauben, M. van Veelen, D. Gossot, and R. Goossens. Application of ergonomic guidelines during minimally invasive surgery: a questionnaire survey of 284 surgeons. *Surgical endoscopy*, 20(8):1268–1274, 2006.