A Tactile Luminous Floor Used as a Playful Space's Skin*

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***Abstract*—This paper describes the hardware and software engineering of the novel tactile luminous floor and how the floor is used as the skin of the playful interactive space Ada, which ran as a public exhibit for five months in 2002 and had 550,000 visitors. Ada's floor consisted of 360 hexagonal 66-cm tiles covering a total area of 136 m^2, each with tactile load sensors and dimmable neon red, green, and blue (RGB) lamps. They were constructed from extruded aluminum with glass tops. A factory automation bus sensed and controlled the tiles. This paper also discusses software for generating visual effects on the floor, for signal processing of the load information, for tracking visitors, and for a variety of games and interactions. Data from single tiles and from tracking are shown.**

***Index Terms*—interactive space, tactile surface, luminous floor, people tracking, gamse**

I. INTRODUCTION

Many luminous floors have been constructed by the entertainment industry for use in discotheques, television studios, and stage shows. They are commercially available from at least five suppliers. These floors enable remote control of the lamps but have no tactile capability. Tactile floors have also been constructed: [1-5] and Selker's group at the Massachusetts Institute of Technology have built tactile floors that can determine the locations of people or their feet with higher spatial or temporal resolution than the floor described here. Their floors were developed mostly for musical instrument input or dance recording.

Ada [6-8] is a playful space intended to stimulate public debate on the future of machine intelligence. It interacts with its visitors using touch, audition, sound, and vision. We think of Ada as a robot turned inside out, with its world being its visitors.

Ada ran as a public exhibit in the summer of 2002 as part of the Swiss National Exhibition. It operated 12 hours a day for five months and had 550,000 visitors—about 3,500 per day. Ada is now maintained as a much smaller version in our laboratory.

In developing Ada, we faced a difficult problem: we wanted a playful space that could interact individually and collectively with many people who moved about freely. Floor-based interaction was an obvious possibility. After building prototypes that tried—not very successfully—to use video tracking and video projection onto a floor, we decided that a tactile luminous floor would offer a better foundation for achieving reliable and effective interaction.

Ada's floor is the principal medium for interaction between the space and its visitors. It consists of 360 hexagonal tiles, each 66 cm across, covering an area of 136m^2. Section II describes Ada's floor-based interactions, Section III discusses the design of the physical tiles, while Section IV describes the floor software. Section V describes the games we developed to run on the floor. Section VI concludes with a discussion of the implications of this development.

II. ADA'S FLOOR-BASED INTERACTIONS

Some of Ada's behaviors that use floor interaction are pictured in Figure 1. Visitors learn that Ada perceives them in a simple reaction when newly loaded tiles generate a transient visual effect, like a surrounding ring of tiles that slowly lights up and then fades away. Visitors learn that Ada knows about them as distinct entities in a more complex interaction, when they are tagged with an individual tile color that they carry with them as they are tracked.

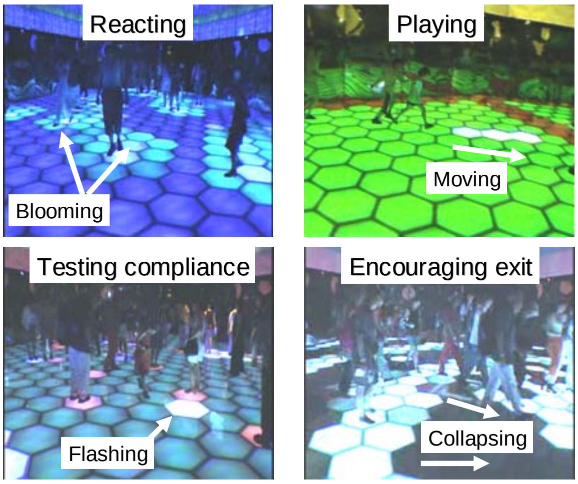

Figure 1 Ada's floor in operation. Clockwise from top left: flowers bloom around newly loaded tiles, children chase a virtual ball, people are encouraged to leave, a visitor's compliance is tested.

Not all visitors pay attention to Ada. To find out whom to spend extra resources on, Ada uses its floor to actively probe a visitor's willingness to interact, a bit like when a dog holds a stick in its mouth and looks at you while wagging its tail. Tracked visitors see a flashing tile next to them. The tile is first presented in the direction the visitor has been moving so that it is more likely to be noticed. If the flashing tile is stepped on, it moves to a neighboring tile. If the visitor follows the tile for a few steps, the space considers that person *compliant*. Compliant visitors receive extra attention: they see a pulsating ring of tiles around them, *light fingers*[1]

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[1] Ada's fingers: steerable theater lights.

*Ada (www.ada-exhibition.ch) was funded by the University and ETH Zürich, Manor AG, and the Velux and Gebert Rüf foundations.

pointing at them, and *gazers*[2] looking at them. In short, they are made to feel special.

Ada also uses the floor to play games with visitors. In the most commonly used game, Football, visitors chase and try to jump on a virtual ball—a brightly lit white tile. The virtual ball skitters about, bouncing off the walls and the visitors. Visitor collisions increase the speed of play. Successful stomping on the ball results in a victory reward: Winners are surrounded by a halo of light that grows and fades away, are highlighted by light fingers and targeted by gazers, and have their image displayed on the *big screen*[3] for all to admire.

III. TILE DESIGN

To enable all of these interactions and to track its visitors, Ada required a floor that was both tactile and luminous. The scale of the project required networking rather than dedicated cables to each sensor or tile. Ada also required an industrial-strength floor that could stand up to thousands of people per day for many months of operation; we were bound contractually by the exhibition's management organization to keep downtime to below 3%. The final tile design was very robust: Ada as a whole achieved an overall uptime of more than 97%, and more than 99% when only floor-based failures were counted.

The final form of Ada's floor tiles was the result of about three years of development of three major prototypes. These were constructed first from wood and Plexiglas using binary 12-V halogen lamps with dedicated cables, then from wood and Plexiglas using triac-controlled incandescent lamps with networked control, and finally manufactured using aluminum, glass, and neon tubes. Figure 2 shows the inside of the final tile.

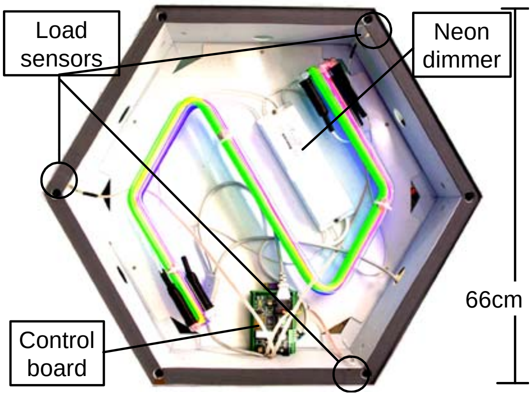

Figure 2 Inside a tile.

A. Network-Controlled

After a long struggle with our own notions of how the tiles could be networked together as cellular automata, we settled on daisy chaining them together using an established factory automation network called INTERBUS[4]. INTERBUS has been widely used in factories since the late 1980s[5] and has several features that make it suitable for use in Ada's floor. It is a master/slave bus: a single personal computer (PC) with several INTERBUS master boards can control the entire floor. Floor installation is greatly simplified because the daisy-chained floor tiles automatically number themselves along the bus. Commodity chips implementing the protocol are readily available. Each node is sensed and controlled at predictable intervals. INTERBUS is good for automation of devices with a small amount of sensor and control data and has robust error checking and diagnostic capabilities.

B. INTERBUS Master Interface

Communication between the higher-level floor-controlling software and the network of floor tiles is via a daemon-like process that uses the INTERBUS master communication interface driver to provide a shared memory interface to the higher-level software. This interface allows development of the higher-level functionality to be decoupled from that of the hardware. The floor tiles appear as a set of shared memory segments. An arbitrary number of processes can read from any segment, whereas only a single process can write to a segment. Separate segments represent the loads on the tiles, the colors to be displayed, and the temperatures of the individual tiles. Ada's INTERBUS-based floor ran with an update rate of about 50 Hz at the driver interface level.

C. Neon Lighting

The floor tiles were illuminated by neon tubes. Neon lighting is a mature technology that is reliable and very power-efficient. It is not trendy like light-emitting diode illumination, but the technologies for production and assembly are known to many lighting firms, such as Westiform[6], the firm that approached us and that we contracted to build the production version of the floor. The main drawbacks of this type of lighting are the delicacy of the neon tubes, the assembly costs, the volume of space required, and the high voltages that must be handled. The lifetime of neon tubes is about 10^4 h, and the main aging characteristic is that the turn-on point—the minimum possible brightness—becomes greater with time. As the tiles age differentially, it becomes more difficult to display uniform dim colors.

Three neon lamps—red, green, and blue (RGB)—illuminate the tiles. Westiform shaped the neon tubes in the sigmoid form shown in Figure 2. The lamp brightnesses are controlled by commercial 3-channel, 80-mA, 990-V neon dimmers[7], which are customized to accept control over an RS232 link. Each dimmer cost about US$200. Power is supplied to the tile as 220 VAC and is locally converted for use by the neon lights and the controller board. Maximum tile power consumption is about 100 W. Maximum tile brightness is about 200 cd/m^2, comparable to that of a computer monitor display.

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[2] Ada's eyes: pan-tilt cameras.

[3] An enclosing ring of video projection screens.

[4] www.interbusclub.com

[5] murray.newcastle.edu.au/users/students/1999/c9518176/interbus.html gives a readable history of INTERBUS.

[6] www.westiform.com

[7] www.toni-maroni.de

D. *Physical Construction*

The design of the tile frames and tops was important because the floor had to withstand heavy pedestrian traffic over months of operation. We also wanted to be able to reinstall the floor at another location relatively easily. Figure 3 shows how Westiform built the tile frames from extruded aluminum. They used two extruded aluminum shapes cut in sections and welded them to form the frame. One piece forms the walls of the frame, and the other forms the legs. Adjustable feet are press-fitted into the legs, and the tile frames are bolted to each other. A ridge and indentation on the leg pieces register the tiles to each other, resulting in a very stable structure. The electronics inside the tile are mounted on a removable hexagonal plate and raised away from the underlying floor level for safety, in the event that water pools beneath the tiles.

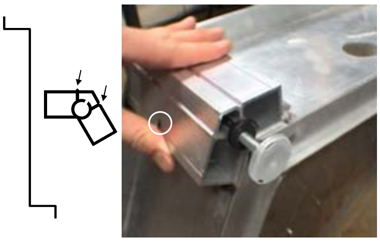

Figure 3 Tile frame profile shapes (not to scale) and outside corner of frame. Arrows show the mating alignment extrusions. The circle shows one of the holes for bolting the tiles to each other.

The tile tops are made from two layers of 8-mm tempered safety glass. Translucent PVB is used to laminate the plates, and an additional 3-mm translucent polycarbonate plate under the glass further diffuses the light to better mix the colors. Each glass top costs about US$100.

Plastic tops were considered because they would have been relatively inexpensive and would have been good at mixing the colors uniformly. However, Plexiglas tops were rejected by the exhibition safety officials because acrylic plastic emits toxic fumes in a fire, and polycarbonate tops of the required thickness were not available. In any case, plastic tops would have become easily scratched and difficult to clean. In addition, glass tops produce much less static electricity. On our prototype floors made with Plexiglas tops, visitors were often painfully shocked due to the buildup of static electricity.

E. *Floor Tile Slave Controller*

A local slave controller in each tile (Figure 4) reads the sensors, controls the neon dimmer to set the lamp RGB brightness, and communicates with the INTERBUS. It also enables self-diagnostics for the lamps and load sensors and has an automatic sleep mode that turns off the lamps and reduces the sensor sampling rate after a period of no networking or load activity[8]. Zero-crossing detection of the power line cycle is used to synchronize lamp brightness changes and sensor acquisition to the line cycle to reduce lamp flicker and sensor noise. Each tile controller board cost about US$70.

The tile controller uses a MAZeT B8052[9] microcontroller with embedded INTERBUS link level controller logic. The firmware is about 800 lines of C code; compiled, it occupies 11 kB of EPROM space.

Power is routed through the floor and to the tiles using commercially available 3-way IEC equipment cables, with one male plug and two female plugs. Approximately 20 tiles can be powered through each such daisy-chained arrangement.

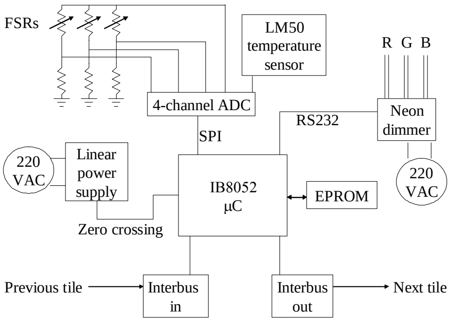

Figure 4 Functional components of floor tile slave controller board.

F. *Load Sensors*

The public visiting Ada ranged from young children weighing about 20 kg to adults weighing over 100 kg. Large adults jumping about can transiently weigh several hundred kilograms. The most important requirement to support accurate people tracking is to reliably detect loaded tiles without falsely detecting unloaded tiles as loaded. Although this may sound like a simple problem, it proved to be quite difficult in the context of a large, long-running public exhibit.

We used force-sensitive resistors (FSRs) as our load sensors after considering several alternative technologies. FSRs are flat and robust, although poorly matched. We mounted three of these, equally spacing them at three corners of the hexagonal tile frame between the frame and the glass tile top and under a 3-mm layer of EPDM (Ethylene~Propylene) rubber. This ring of rubber supports the glass and is also important because it divides the force seen by the rather sensitive FSRs to a usable range for human weights. FSR conductance increases monotonically with the applied load, approximately as a square-root relationship. FSRs are effectively single-sourced[10] and cost about US$5 each. Although three sensors are sufficient for sensing the load on a single tile, six would have ensured that there were no blind spots on the assembled floor and would have resulted in more reliable tracking of visitors who occasionally stand on tile intersections where there are blind

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[8] Two tiles have been continuously powered in T.D.'s office for the last two years, mostly in this sleeping state.

[9] Now obsolete. New designs should use a microcontroller that can communicate with an INTERBUS SUPI3 interface chip, sold by Phoenix Contact (www.phoenixcontact.com) for about $5.

[10] www.interlinkelec.com. Another source recently discovered is www.tekscan.com.

spots in the load sensing. (Most intersections are covered by one or two load sensors, but owing to the pseudo-random assembly of tiles and floor, there are some intersections with no load sensor.)

The tile measures the load on its glass top by forming a voltage divider with each of the three FSRs (Figure 4). FSRs can be damaged by sustained continuous current, so they are only powered during readout, with an active duty cycle of < 5%. The master controller computes the equivalent FSR load from the voltage divider values and sums the three load values to form a single average tile load value. This value is linearly related to the load applied to the tile.

G. Load Signal Processing

The tile-to-tile variation in the unloaded tile load output is about one-third of the full-scale value. Manufacturing differences in the tile frames and tops cause most of this huge mismatch by applying varying amounts of the load from the glass to the frame instead of to the FSRs. Moreover, the excitation of the neon tubes by 1 kV, 20 kHz voltage pulses causes a significant impulsive noise spike if a neon excitation pulse occurs while a nearby load sensor is being read.

Active visitors can shift the glass in the tile frame, resulting in small but significant shifts in the baseline tile load. As the tile rubber between the FSRs and the glass ages or becomes compressed by sustained loading—which occurs, for instance, near an exhibition entrance—the baseline tile loads slowly change.

This impulsive noise and non-stationary tile-load-sensor mismatch require filtering the raw load signals before determining whether tiles are loaded. Because it is very inconvenient to change the EPROM'd tile firmware, filtering is computed on the floor controller but is effectively independent for each tile. The impulsive noise is first removed by a median filter with a window of seven to nine samples.

The floor controller then continuously learns an estimate of the unloaded state of each tile, which consists of a value for each tile that is subtracted from the raw load to produce the filtered load; a fixed threshold then determines whether the tile was loaded. This single global threshold can easily be set so that a 5-kg force applied by a few fingers pushing down anywhere on a tile (except directly over one of the corners without a load sensor) is enough to trigger a loaded state over any of the floor tiles.

The estimate of the unloaded state of the tile adapts slowly upward over a time scale of minutes while the tile is loaded, and rapidly recovers downward over a time scale of seconds when the tile is unloaded. The adaptation time scales for loaded and unloaded states are different to slowly forget loaded states and rapidly recover from unloaded states. This asymmetry is necessary so that tiles can become resensitized rapidly to small loads (active children) while only slowly forgetting about large loads (adults lingering in one place).

These learned tile unloaded states are saved persistently to ensure rapid startup. They constitute one of the forms of long-term memory in Ada. This continuous adaptation proved absolutely essential for ensuring reliable visitor interaction.

The raw sensor values and combined raw tile load values from two tiles are shown in Figure 5. A person has stepped from the first tile to the second and, while on each tile, has moved around to different locations on the tile. Although the individual sensor values fluctuate considerably depending on where the feet are located, the combined values remain relatively constant, indicating that the combined value is useful for detecting a loaded tile. The remaining variability in the load value results from the person's movement and the use of three rather than six FSRs.

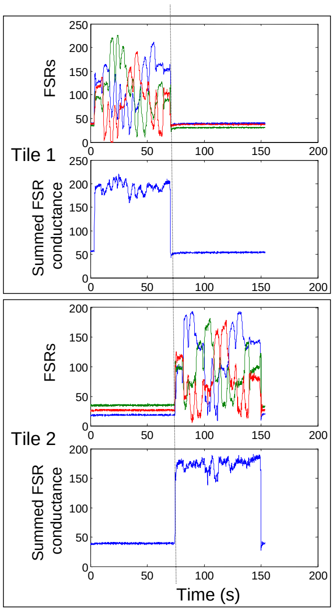

Figure 5 Tile sensor and load characteristics.

Linearity characteristics of the computed loads are illustrated in Figure 6, which shows measurements from the same two tiles using a range of three loads generated by two people standing either alone or together on the tiles. Although the tile DC values and gains are different, each tile's response is linear in the applied load.

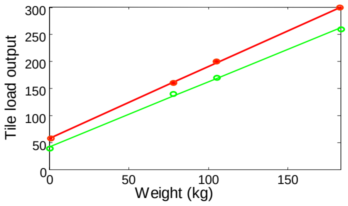

Figure 6 Tile load linearity.

Although binary detection of loaded tiles is the most important use of the load information, we also use a tracked person's average load to estimate the height of their heads to better aim Ada's gazers to look at them, and we use the analog tile loads in one of the games to measure visitor dance movements.

IV. FLOOR CONTROL SOFTWARE

Ada’s software is a heterogeneous mixture of procedural code and neural networks. Most of the procedural code, including nearly all the floor code, is written in Java. We chose Java for its high productivity, debugging tools, and remote procedure call support. Hard real-time performance was not critical for this exhibit, but we were pleased by Java’s ability to deal with a large soft real-time environment.

A single PC handles the entire floor. It runs the C++ INTERBUS process (13 classes, ~6,500 lines of code) and a Java floor process comprising about 80 Java classes with about 20,000 source lines of code. Ada’s exhibition-floor update rate running on a 1-GHz Pentium processor under a load of about 20% was about 15 Hz.

A. Rendering

Traditional two-dimensional image rendering is not really appropriate for controlling the colors of Ada’s tiles because nearby tiles dominate the visitor’s view. Instead, we developed methods for rendering fluid localized patterns of activity that could be linked to a tile or to a tracked visitor. For example, tiles can be lit, pulsated, or flashed. Pulsating, expanding, and contracting rings and blobs can be displayed. Directional effects imitating bullets and lasers can be generated. We also developed a general set of dynamic patterns that can be displayed on floor regions, such as pulsating or cycling floor colors, drifting sinusoidal gratings, and perimeters of floor regions. These local and global effects are the only outputs onto the floor.

Created visual effects are placed on a list and are updated at every floor cycle until they expire or are removed. Each effect knows how to update itself, how to compute which tiles should be affected, how to set their brightness, and so forth. A large number of parameters such as color, alpha, rate, size, rise, and fall time control the dynamics of the effects.

Reactive effects that are automatically created on freshly loaded tiles constitute most of the behavior of Ada during its simpler behavioral modes—like sleeping or encouraging visitors to leave.

B. People Tracking

The primary objective of Ada is to identify individuals and playfully interact with them. To enable complex interactions, Ada must track visitors so that labels assigned to them—a special color or pattern—can travel along with them or a gazer or light finger can follow them.

The matching-based tracking algorithm is applied during each load sensor update cycle. The filtered weight sensor values (as described earlier in Section III.G) determine whether a tile is loaded or not. All tracking is based on these binary loaded tile states. Tracked persons are always assigned to a single tile. Tracking starts when a tile not belonging to a tracked person is loaded for a few hundred milliseconds and is surrounded by unloaded tiles. When a tile assigned to a tracked person becomes unloaded, nearby loaded tiles that have not been loaded for too long are assigned as possible destinations of that person. (Tiles that have been loaded for too long are considered to belong to other visitors.) A list is built of all possible destinations of all tracked persons. This list is pruned by matching person to destination. As each match between target and destination is made, the corresponding objects are removed from further consideration.

If no match for an unloaded tile is found, a timeout is started because the visitor could be in the air. If a proper match is found within the timeout, then tracking continues; otherwise, the tracked person is discarded. Such situations also allow tracked visitors to generate two kinds of gestures, a *hop* and a *pogo*. A hop is a jump through the air to another tile, while a pogo is a jump in the air that lands on the same tile. These gestures are used in games like Gunfight, which is briefly described in Section V.

Clearly, there are situations when tracking fails—for instance, when two tracked people come together to stand on a single tile. Then one of them is discarded. But for the most part these situations do not occur, because people (at least adults) maintain a significant personal space.

The result of the tracking algorithm is a list of tracked people maintained by the floor server process.

The characteristics of tracking based on binary loaded tile states are illustrated in Figure 7, which shows a top view of the floor over a period of about 2 s. Tiles labeled with black crosses were loaded and those labeled with red were loaded and linked to tracked persons.

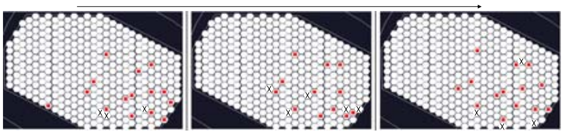

Figure 7 Sequence of tracking states.

Statistics about the reliability of tracking are difficult to quantify because conditions during the exhibition were extremely variable, and objective measures were hard to determine. We show some representative data in the form of recorded tracker paths in Figure 8. Baebler’s analysis [9] of correlated floor-tracking data and recorded video showed that most tracking errors were related to unreliable detection of loaded tiles—probably due to the use of three rather than six FSRs per tile—rather than to incorrect matches by the tracking algorithm.

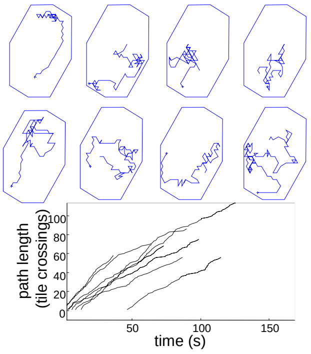

Figure 8 Representative tracker paths over 2-min period, Oct 19, 2002, along with tile crossing data vs. time.

Our simple matching-based tracking algorithm does a credible job in tracking visitors because at the moment that tracked people unload their assigned tile, they have a very limited number of possible destinations. It also easily runs in real time. It performs well when the space is uncrowded (< 5% loaded tiles) or when visitors want to interact with Ada. Such visitors usually step on single tiles and keep a polite tile distance from each other. When the space is uncrowded, even completely naive visitors are tracked fairly reliably over distances of many tens of tiles. When the space is crowded, a knowledgeable visitor familiar with tracking can also be tracked with high reliability. Tracking is degraded in instances where children run wildly through the space trying to step on as many other people's tiles as possible, or by crowded conditions, when people tend to ignore tile boundaries.

V. GAMES

Some high-level behaviors and the Football game were described in the introduction. We also developed a number of explicit games that were suitable for use on this floor.

- Our version of Pong splits the floor into two halves, with a virtual paddle on each half of the floor collectively controlled by the center of mass of the player locations on that half of the floor, leading to spontaneous cooperation among strangers.
- Boogie is a collective dance game. The power spectra of the analog load information from active dancers are analyzed to extract dominant frequencies, and a consensus drives the overall rhythm and volume of the dance mix.
- Gunfight labels tracked players with lit tiles; players use hop gestures to shoot virtual bullets toward other players to extinguish them from the game. Players can use pogo gestures to temporarily surround themselves with an impenetrable shield. The surviving victor is rewarded with impressive collapsing rings of green covering the entire floor.
- In HotLava, which was inspired by a television game show, two players compete to find their way across the floor on a hidden path. If they step off the path, their half of the floor flashes an angry red, and they must start over from the beginning.
- Finally, in a simple but effective game called Squash, the floor is randomly illuminated with two colors. Illuminated tiles are extinguished by being stepped on. Each team competes to see who can first extinguish all the tiles of their team's color. This game is good for a battle of the sexes.

VI. DISCUSSION

Ada's floor can be a lovely sight; for instance, when a softly pulsating blue background is combined with a fading rose-colored drifting grating, and visitors' steps cause soft cyan flowers to bloom all around. It is a captivating experience for visitors to realize that they have successfully gained Ada's attention and played with her.

The tactile surface also provides an interesting environment to study single and multimodal people tracking. Floor-only tracking could be enhanced. For example, we could use the individual sensors in each tile to localize loads to sub tile resolution (especially if we had six sensors per tile), and we could apply probabilistic methods. Tracking can also be linked back to sensor calibration by using tracked persons as sources of calibration for individual sensor and tile gains. Preliminary investigations along these lines have indicated that all these topics are trickier than they may appear for reasons we do not have room to explain here.

To our knowledge, this is the first floor built that is both luminous and tactile, or that allows individual tracking of multiple persons. The high cost (US$800/tile) of the custom-produced present floor limits its applications, but Ada demonstrated that it could be used reliably for novel and fairly sophisticated public interaction with more than 550,000 naive visitors over five months of continuous operation. This tactile luminous surface offers new forms of human-computer interaction.

ACKNOWLEDGMENTS

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