FootNotes: Personal Reflections on the Development of Instrumented Dance Shoes and their Musical Applications

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Abstract

This paper describes experiences in designing and developing an extremely versatile, multimodal sensor interface built entirely into a pair of shoes. I discuss the system design, trace its motivations and goals, then describe its applications in interactive music for dance performance, summarizing lessons learned and future possibilities.

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1) The Inspiration

Although the idea of instrumenting shoes for interactive music performance had crossed my mind before, the moment at which I decided to pursue this project can be traced to a demonstration that I attended with my Media Lab colleague Tod Machover in November of 1996. We were visiting some of our research sponsors and colleagues at a Yamaha development laboratory in the Shinjuku section of Tokyo, where they showed us the latest version of their *Miburi* musical controller [1]. The *Miburi* is an electronic vest, with bend sensors at various joints to monitor dynamic articulation and a pair of handheld controllers that sport a velocity-sensitive keyswitch for each finger (to see a video clip of the *Miburi* in action, visit: http://www.spectrum.ieee.org/select/1297/miburi.html or http://www.media.mit.edu/~joep/SpectrumWeb/captions/Miburi.html - it is no longer manufactured). They had modified the *Miburi* system shortly before our visit to include electronic insoles with piezoelectric triggers at the toe and heel for firing percussive sounds and enabling electronic tap performance. A cord extended from these insoles (between heel and shoe) and ran up to a beltpack unit, which collected data from the entire ensemble and transmitted it wirelessly to a nearby receiver and synthesizer-mapper. Figure 1 shows a photo that I took of the Tod and the Yamaha staff demonstrating the *Miburi* system that day. Although the *Miburi* seemed to be a difficult instrument to master (especially with the precise, semaphore-like movements that its designers had choreographed for playing notes - it seemed to be intended as a song-playing interface rather than a continuous multimodal controller), these musician/dancers were able to perform impressively (and aerobically) once the sensors were properly adjusted and calibrated.

I'd built several different kinds of electronic music controllers by that time (Tod and I were actually in Tokyo for a run of our then-new *Brain Opera* installation, for which I'd designed the sensor and interface systems [2]), and was thinking about new steps to take in this area. As we had recently decided to sponsor the first IEEE Conference on Wearable Computing at the Media Laboratory and host a concurrent Wearable Computing Fashion Show in the fall of 1997 (see: http://www.media.mit.edu/projects/wearables/out-in-the-world/index.html), most of the Media Lab was mulling over different pieces of technology that could be presented at the conference and worn or exhibited in the show. Thinking along these lines and seeing the *Miburi* shoes in performance inspired me to take a fresh look at footwear.

Although electronic tap shoes, as in the *Miburi,* are an old idea and have appeared in several incarnations, there are many more degrees of expression possible at the foot of a trained dancer that such limited interfaces entirely miss. In different applications, one tends to see particular sensor families used exclusively for certain types of footwear (e.g., piezoelectrics for dance, pressure sensors for medical or podiatric applications, inertial sensors for sports and pedometry) - the concept of measuring *everything* at the foot with many different kinds of sensors is quite unusual. Interfaces for human-computer interaction and virtual reality generally throw lots of technology at the hands, ignoring the feet. Additionally, having sound only produced when the foot is in contact with the floor seems to be extremely limiting; I envisioned a pair of shoes that would respond well to free gesture in the air while retaining several degrees of control when contacting the floor. Additionally, having the shoes tethered with cables to the beltpack (as in the *Miburi*) was undesirable; wireless communication directly from each shoe to the remote music system would be much more convenient and robust.

2) Hardware Development and Experiences

Returning to the Media Lab, I wrote up a design study for such a system [3], including every different type of sensor that I could imagine using and integrating them appropriately into the shoe. This was very much an engineer's approach, as I knew lots about sensors but essentially nothing about dance. I thus worked out a collection of instruments that measured every movement that I thought was possible and readily detectable with all electronics mounted right on the shoes themselves. Fig. 2 shows this concept in detail - it involved 7 different families of sensors measuring pressure at 3 points in the sole, bend of the sole, tilt and foot swings, angle of the foot (via an electronic compass or gyro) and position of the shoe with a sonar transponder or laser tracker. After being notified that the paper was accepted at the upcoming IEEE Wearables conference, I was committed to realize it, hence recruited an MS student to help build the hardware [4]. We completed our first pair of shoes just in time for the wearable events in October of 1997.

The actual shoe that we made is shown in Fig. 3. We postponed the idea of distributing the sensors and electronics throughout the shoe (e.g., burying them in the heel, etc. as suggested by Fig. 2), instead simplifying by putting all of our systems in a sensor-laden insole and side-mounted electronics card. By the time we had finished, we wound up implementing essentially all of the sensors from Ref. [3], even adding a few more. Upon the advice of our MIT dance student collaborator, we selected a Capezio "Dansneaker" for our first shoe, which offered ample room to mount our electronics card on the outer side, where it interfered minimally with the dancer. As can be seen in the photo of our first circuit card (Fig. 4), this was very much an initial prototype. It was entirely functional, however, at least for a couple of months, after which repeated repairs and modifications had introduced too much fragility. Figure 5 shows a block diagram of all the sensors. This device used piezoelectric foil strips (A,B,C) in the insole to measure dynamic pressure at 2 points in front of the shoe (below the balls of the feet) and 1 point at rear (beneath the heel). A bi-directional resistive bend sensor (D) measured the bend of the sole in both directions (the Capezio is nicely flexible each way), and a copper strip (E) at the bottom of the insole functioned as an electric field pickup. We could thus place flat electrical conductors (e.g., metal screen or plated foil) atop the stage at various locations and detect when the dancer was standing on them and measure the height of the shoes above (via capacitive coupling [5] as in a Theremin) when elevated. The electronics card on the shoe included a 2-axis low-G accelerometer (H: for sensing foot tilt and swings), a rate gyro (G: for measuring twists about the ankle), a 2-axis electromechanical compass (K: for measuring the foot angle in the Earth's magnetic field), and a 3-axis, high-G piezoelectric accelerometer (F: for sensing jumps and foot stomps). Likewise, there was a small sonar pickup (J) on this card - as in Fig. 2, one could ping from several locations around the stage and locate the shoes by triangulation. A small "PIC" microcomputer (L) collected the data from the various sensors and produced a serial data stream (updating all parameters 50 times per second) that was sent right off the shoe by a small RF transmitter (N) to an offstage basestation and PC system that generated MIDI commands for driving the music synthesizers. We fit a small, 6-volt lithium camera battery (M) onto this card as well, which was able to power the shoe systems adequately for up to a few hours at a time. The details of this system were published in [6] and [7].

Despite its jury-rigged appearance (Fig. 4), both shoes were fully functional and were actually used in performance at the Wearables Fashion Show by our student dancer, Yuying Chen (Fig. 6). Our software only dealt with one shoe at the time, however, and the sonar wasn't then fully implemented in the onboard PIC code due to complexity with interrupt protocol and synchronization. Likewise, the shock accelerometer's response to jumps and kicks was too fast to be reliably detected at the 50 Hz sampling rate, hence it was supplanted by a floppy piece of piezoelectric foil that was soldered onto the circuit card and would flop around when the dancer abruptly moved their foot, producing an easily discerned signal.

Although these shoes worked well for the days of demonstration and performance in October 1997, they rapidly deteriorated (e.g., pieces kept falling off, breaking more and more of the circuitry in the process) and were eventually impossible to repair adequately. A dancer's foot is indeed a hostile environment for sensitive electronics, and as we've been reminded repeatedly by experience, everything needs to be well attached or latched down - anything that can move will sooner-or-later break off.

Over the next couple of years, we designed a series of new electronics cards, taking into account the lessons learned from the prototype. We used analog pulse-stretching techniques on the shock accelerometers, enabling them to reliably detect jumps and kicks with the 50 Hz sampling rate, eliminating the troublesome piece of floppy piezoelectric foil. We replaced the 2-axis electromechanical compass, which although very simple to integrate, was too slow and extremely unreliable (e.g., the gimbals would start to stick after a dancer pounded their feet for a few hours), with a solid-state, all-electronic, 3-axis magnetometer. We made the two pressure sensors at the front of the shoe respond to continuous pressure (to sense the dancer smoothly as they press forward) and kept the piezoelectric sensor at the heel (where dynamic pressure was more relevant). At the suggestion of our first choreography collaborator (Byron Suber from the Cornell University's Dance Department), we added another pressure sensor at the tip of the shoe, to sense the dancers pressing the toe down on the floor when the foot is pointed vertically - a very clean gesture, hence appropriate for triggering events. We moved the battery off the circuit card, freeing more room for electronics and allowing us to use a larger (and more commonplace) 9-Volt alkaline battery, which provided over a half-day of stable performance and useful life. Although fairly simple modifications to the power conditioning circuitry could improve this by more than a factor of two, the half-day of life was adequate for dance practice and performance. Similarly, modifications to the onboard PIC code and the base stations enabled the sonar to work well for both shoes (ranging out to 25 feet from up to 4 pinger locations) and error-correction and "glitch-detection" algorithms running on the base stations and PC enabled clean reception of sensor data. The revised shoes are described in [8] and detailed in [9], and a picture of our current model is shown in Fig. 7, with a close-up of the card in Fig. 8. As Byron had selected costumes for our collaboration at the American Dance Festival accordingly, we moved from the Capezio's to a Nike Air Terra Kimbia jogging shoe upon his suggestion.

This electronics card, mounted against a metal backplate (riveted to the shoe) and covered with a protective Plexiglas shield, is very robust and holds up extremely well. There were a few notable mishaps along the way, however. The first was during a dress rehearsal for a piece that we did at a Wearable Computing Fashion Show for NIKOGRAPH in Tokyo at the end of 1998. We were working with a gymnast, who was performing cartwheels and leaps while wearing our shoes. This was generating fantastic data, which we were using to launch and sculpt an array of corresponding sounds and musical events. Upon landing hard from a particularly high backflip, however, I noted that a large piece of hardware flew off each shoe, hitting guests in the audience and stopping the data flow (and music) in the process. I was quite relieved to find out that the guests were fine and these were merely the 9-volt batteries (with little of the other circuitry carried along), hence we from thereon distrusted the battery clamps and wire-tied the batteries on before each performance. Another such event was at our performance at the American Dance Festival during the summer of 1999. When we started the second of two pieces in the program, I noted that one shoe was not responding at all, hence I stopped the show and inspected the dancer's shoes, becoming horrified to discover that the PIC microcomputer chip had completely fallen out of its socket at the end of the previous piece and was now lost somewhere on the stage, perhaps crushed. Fortunately, it had fallen near one of my students (who had heard it actually hit the floor), so we quickly recovered (after occupying a minute with most of us combing the stage for the missing chip, which the audience found quite amusing) and then finished the performance without further incident. Our shows from then on used a piece of foam tape to keep the PIC pressed firmly into its socket (the PICs that we used at the time were unable to be in-circuit programmed, hence needed to be socketed to allow easy removal during development).

The only piece of the system that still has significant reliability problems at the moment is the sensor insole. It's made from a standard "Dr. Scholl's" foam insert, with the various sensors slid into slits cut in the insole and held in place with tape. The standard insole that comes with the shoe is placed atop the sensor insole, providing protection from abrasion, moisture, etc. The sensors are soldered to standard ribbon cable, which exits through a hole in the rear of the shoe and connects to the sensor board. After a dancer uses the shoes for a several days, we find breakage often occurring at the places where the wires solder to the sensors, probably due to the wires repeatedly binding and pulling as the sole bends back and forth in performance. We are looking at two techniques to avert this - e.g., gluing the wires into place around the point where they join the sensors (and providing for ample strain-relief) or abandoning the wires all together and moving to a flex-circuit insole, with sensors soldered directly onto conductors plated onto a common bendable substrate, such as Kapton. An example of the latter approach is the new sensor insole shown in Fig. 9 that resulted from a collaboration with the National Microelectronics Research Center (NMRC) in Cork, Ireland.

Although the electronics occupy a considerable area along the outer side of the shoe, they don't add a large amount of weight. The material introduced here does constrain the motion of the dancer somewhat, but only for particular motions (e.g., rolling the foot outward against the floor). Of more impact is perhaps the stub antenna protruding from the back, which can interfere with the dancer's ankle when rotating and bending the foot. Although the stubs help data reception significantly (at least when not shadowed by the leg), the onboard transmitters are sufficiently powerful to allow them to be replaced with loop antennas that can be integrated much more innocuously into the shoe. After a bit of accommodation, the stubs have worked fine with the performers that have used our system thus far. Future editions will probably use smaller antennas (at higher transmit frequencies) or embedded loops.

3) Applications in Dance and Performance

From the moment we first began making operational hardware, we've been pushing this system into demonstration performances with different dancers and artists, exploring its utility in various domains. With 50 Hz state updates, our device is too slow to work well with fast percussive dance styles, such as tap or Irish step dance. With all of the different sensing modes, however, it does lend itself well to modern dance styles based more upon free gesture and less upon precise timing. The PC-based software that ran our demonstrations was all written in C++, using the "ROGUS" MIDI library that was developed for the Brain Opera. My student Kai-yuh Hsiao was the main player throughout most of these mappings; as he wrote the PC software and implemented most of the music, he deserves special mention here.

Our philosophy in musical mapping has mainly been one of "direct manipulation" [10], where fairly simple pattern recognition routines running on the sensor data would fire and modify sounds in accordance with a deterministic set of rules that could be learned by the dancer. This stands in contrast to many other interactive dance projects where complex algorithms are written to extract higher-level gesture from the sensor data. Our technique tends to put control into the hands of the dancers, arming them with a palette of basic sound-vs.-action rules that they can piece together to give a performance. When the computer abstracts too deeply, the cause-effect relationships (between an observed action and its sonic outcome) can begin to separate, potentially imposing a break between the audience and performer. Our philosophy has been to give the dancer access to a sufficiently large selection of simple sound-action mappings to enable them to assemble and deliver an engaging performance, rather than to abstract too deeply into a more sophisticated level of gestural determination.

By putting so much control at the dancer's feet, we have introduced a large asymmetry into the balance of bodily expression - we have no systems currently tracking upper body motion in our demonstrations, hence all action must be directed through the feet to produce a sonic response. With the exception of electronic tap shoes (which, again, weren't in the design scope of our system), the opposite is usually true for interactive dance, most of which seems to use video tracking [11], which responds well to the motions of the basic limbs but delivers little information on what's happening right at the feet. Our system generally required some adaptation from many of our dancers, who learned to augment upper-body gestures with corresponding foot activity to produce appropriate sounds.

Figure 10 shows a montage of photos from several of our dance projects. More photos and video clips that show excerpts from all performances are available from our project website (http://www.media.mit.edu/resenv/danceshoe.html) - smaller video clips can be downloaded from (http://www.research.ibm.com/journal/sj/393/part1/paradiso.html). I will touch on the musical mappings below; more details are provided in Ref. [9].

The first musical mapping that we constructed (for the 1997 Wearables Conference) ran atop a continuously running musical sequence. The shoe (only one was active then) added notes, embellishments, and simple effects atop the rhythmic grid. The rule set was extremely literal (e.g., pressure sensors play notes, bend transposes, jumping makes a crash sound, twirling produces wind effects, tilting crossfades sequenced voices, etc.), hence easy to master. This project also set some fairly intuitive precedents that we continued throughout all of our experiments; e.g., playing notes on the pressure sensors (high notes up front, bass on the heel), bend doing transposes (up and down with bend direction), and shock sensors triggering large sonic transients. The insole pressure sensors produced the dominant sounds while dancers moved about - they could be played deliberately (almost like a stripped-down keyboard) when the foot was rocked (a very subtle motion that could be done entirely at the foot) or "parasitically" respond to the dancer walking and prancing about.

After finishing the fully functional pair of Nikes in 1998, we began working with other kinds of performers - first the gymnast for the Tokyo Wearables fashion show mentioned earlier and later a juggler, again in Tokyo but now at the 1999 Toy Fair. We designed some simple explicit recognition systems for the gymnast; e.g., to detect when he was doing a handstand and launch a drum roll in response, ending in a large orchestral hit when he landed. We also began working more with textural sounds introduced with shoe tilt and twirl (e.g., playing a rush of notes with velocity dependant on the tilt angle or twirl rate), which provided a much richer-sounding and engaging response. The juggler used the shoes in an entirely different fashion, moving his feet to add emphasis and sonic augmentation to his juggling action (a clear example of slaving the lower body to what the upper body was doing). Although the gymnastic performance was the only project that we've done thus far with an athlete, it points to a fascinating direction for the future of broadcast sports, where compact sensor clusters like our system can be innocuously fixed to the player's gear, enabling various kinds of mapped content to be generated directly by data from the point of action instead of extracted later from interpretation of a much more abstracted video sequence.

Our system was now working sufficiently well to engage professional choreographers and dancers, so we next began working with Byron Suber from Cornell University (currently at Tulane University in New Orleans; Byron was introduced to us through his composer colleague at Cornell, David Borden). Starting with the gymnast's mapping, we were able to create an effective dance demonstration after spending a day with Byron, adjusting and tweaking the sounds associated with various actions, bringing them into aesthetic accordance with the movement that generated them. Here we began to segment our space up into discrete regions; when standing on the electric field transmitter plate, the dancer could play with droning sounds, adjusting timbres as the foot moved and rotated. Off this plate, the drone would stop and the dancer had full access to the notes and other sounds triggered by the various sensors. We likewise dispensed with the background pedestrian sequences; when the dancer stopped moving, the sounds would stop evolving or silence all together. This restored a greater sense of immediacy to the performance and helped to maintain the audience's perception of what the dancer was controlling.

We next worked with Byron on a much more complicated piece, which we demonstrated in July of 1999 at the American Dance Festival. Here we worked with a pair of dancers (each wearing one active shoe) and used full-up sonar tracking to zone the dancers about the stage and produce position-dependent effects and triggers. If the dancers stayed in one position long enough, a looped background sample of prerecorded music would begin, with the selection that was played depending on their particular locations. Once such a sample started, the dancers could pull it around by tilting their active foot, which would progressively introduce pitch bend, vibrato, reverberation, or resonant filtering, depending on which foot was moved about which axis. This mapping was quite complicated, being designed for a piece that Byron had choreographed around a grid centered on the electric field transmitter plate, which still silenced all other sounds and produced drones when the dancer stood on top. Byron's dancers, students at Cornell, learned the piece by heart, and danced it entirely as planned. During the piece, the system responded appropriately, with the exception of an occasionally jittery sonar caused by the failure of a serial port on the host PC just before showtime. This composed piece, however, lacked the impact of the improvisations that followed, where we had guest choreographers try the shoes on and spend a few minutes following their whims and dynamically interacting with the generated sounds (not entirely unexpected, as we designed the shoe system mainly for improvisation). During this segment, the contribution by Mark Haim was easily the most engaging. Mark has displayed an exceptional affinity for this system, perhaps because he is both an accomplished musician as well as a dancer/choreographer, hence is at home in both of the worlds that the shoes address.

We invited Mark to MIT's Kresge Auditorium later that year to give a performance at a large event that the Media Lab was hosting (http://www.media.mit.edu/Sensibles). We made a few simple modifications to the ADF mapping (e.g., repaired the jittery sonar, defined several loads of different pressure-sensor-triggered sounds that would toggle with each visit to the central electric field pad, added a range-dependent reverberation effect to give a dry sound close to the center of the stage and a progressively wetter sound with increasing distance, and triggered the looped samples of music only when the front pressure sensor was pushed down - a very deliberate action), and spent only a few hours working with Mark to refine and tweak the parameters before going live before the audience. This resulted in the most interesting work that we've thus far done with this system; a RealVideo clip of the entire performance is posted off http://www.media.mit.edu/resenv/danceshoe.html .

4) Conclusions and Future Directions

When I first designed this system in the study that I wrote up in 1997 [3], I suspected that I was going way overboard on the sensor suite, incorporating many more sensors than needed. After using the system in our various projects, however, this was proven to be totally wrong. As it turned out, every sensor was useful. Although there's some overlap between measurements, they all respond somewhat differently to different stimuli, and with the appropriate mapping, dancers can exploit all degrees of freedom effectively. Likewise, extra sensor measurements help enormously in resolving ambiguities. One example, for instance, is with the sonar. When a dancer jumps and lands hard, a false sonar response occasionally results from circuit card vibration and any associated metallic clanging. The jump is also detected, however, by the shock accelerometer systems, which can provide an effective veto to the spurious sonar signal.

With 16 parameters streaming from each foot, manually constructing these mappings at the sensor signal level was a considerable effort, involving complex ideas and assumptions on our part along with time-consuming trials and practice from the dancers. Although we have avoided higher-level gesture recognition, it could offer a solution to this dilemma, which will become more acute as we add more sensors and/or performers to the system. Here, the composer/choreographer would work in a higher-level gestural space, with parameters more relevant to dance or music (including perhaps estimates of affect and emotion [12]).

A next logical step is the instrumentation of entire dance ensembles, developing even more compact hardware packages that can be worn unobtrusively at the wrists, feet, and other relevant areas of the body without requiring connections to a central "hub" - e.g., a beltpack or backpack, as is conventional in most sensor-based interactive dance done today. To address this, we are exploring the miniaturization of our hardware, together with appropriate power management schemes to reduce battery size and appropriate mechanics to allow rapid configuration to various individuals (at present, for example, our electronics are somewhat permanently mated to a size 9 shoe).

Our current system implements its wireless telemetry in a very basic fashion, using a different transmit frequency for each shoe. We are now developing a high-bandwidth channel-shared scheme for stage performance that will relay data directly from the lightweight sensor nodes to a "heavy" offstage basestation, as depicted in Figure 11. As mentioned above, considerable challenge exists here in the areas of data handling, sensor fusion, feature recognition, and, of course, musical mapping.

The Expressive Footwear System that I've described in this paper is at the intersection of several genres. It is both a tactile and free-gesture musical controller. Likewise, it solidly spans the boundary between musical performance and dance - an intersection that interactive dance systems have approached for years now. The best performers in this space tend thus to be comfortable on both sides of the border; e.g., in addition to being competent dancers it helps for them to be capable improvisational musicians.

5) Acknowledgements

Many people have contributed to the success of this system. In particular, I'd like to thank the students in my *Responsive Environments Group* here at the Media Lab who worked on the project, namely Kai-yuh Hsiao, Ari Benbasat, Eric Hu, and Ari Adler. Likewise, the input from our artistic collaborators has been crucial, especially Yuying Chen, Mia Keinanen, Byron Suber, Mark Haim, and Mark Dampolo. We likewise thank our collaborators at the National Microelectronics Research Center (NMRC) in Cork, Ireland (namely Cian O'Mathuna and Kieran Delaney) for providing the flex-circuit insole.

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Figures

Figure 1: Tod Machover trying the *Mibui* interface with some expert coaching at a Tokyo Yamaha Lab

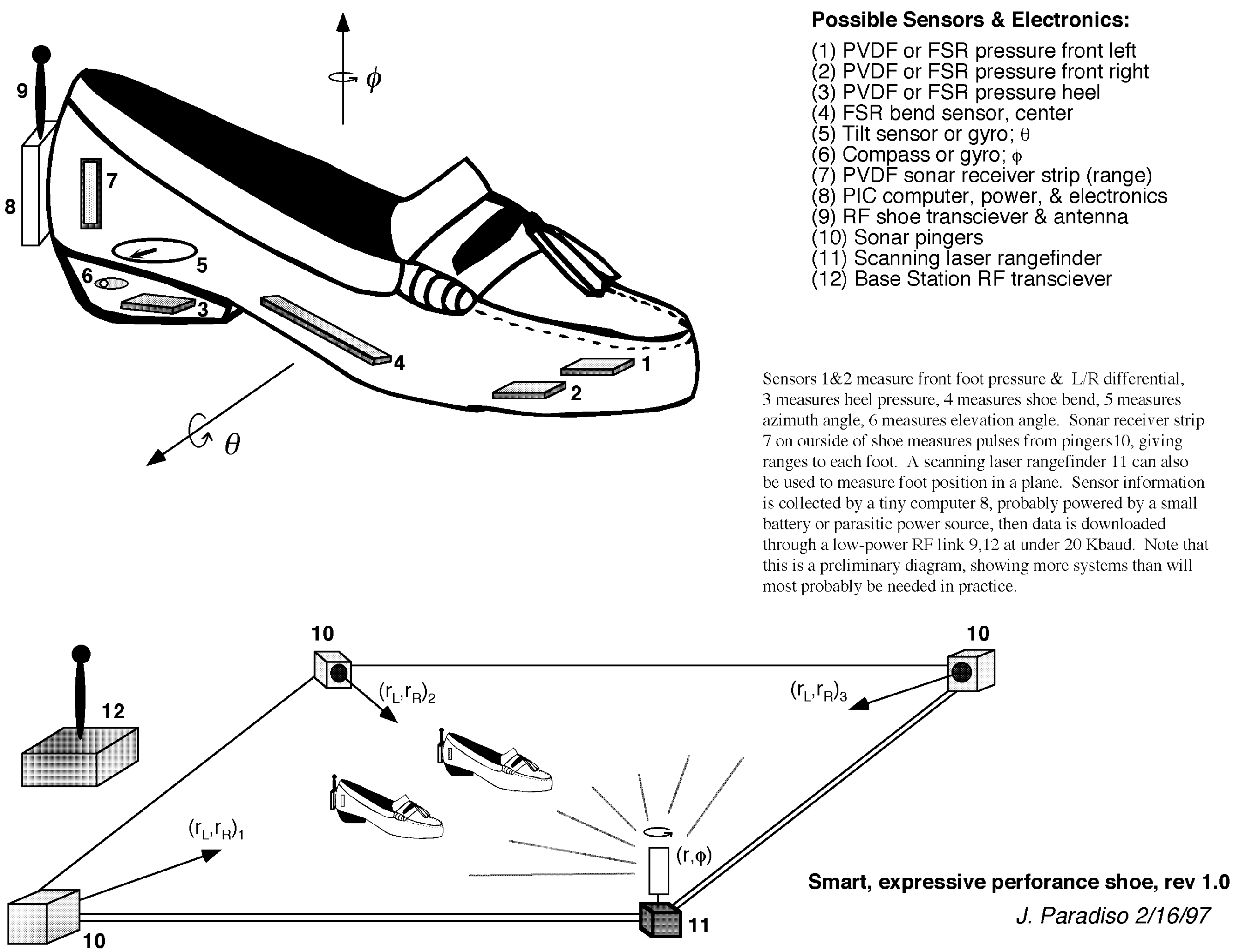


Figure 2: Initial conceptual diagram for original shoe system study

Figure 3: An original prototype shoe, as demonstrated in the 1997 Wearables events held at MIT

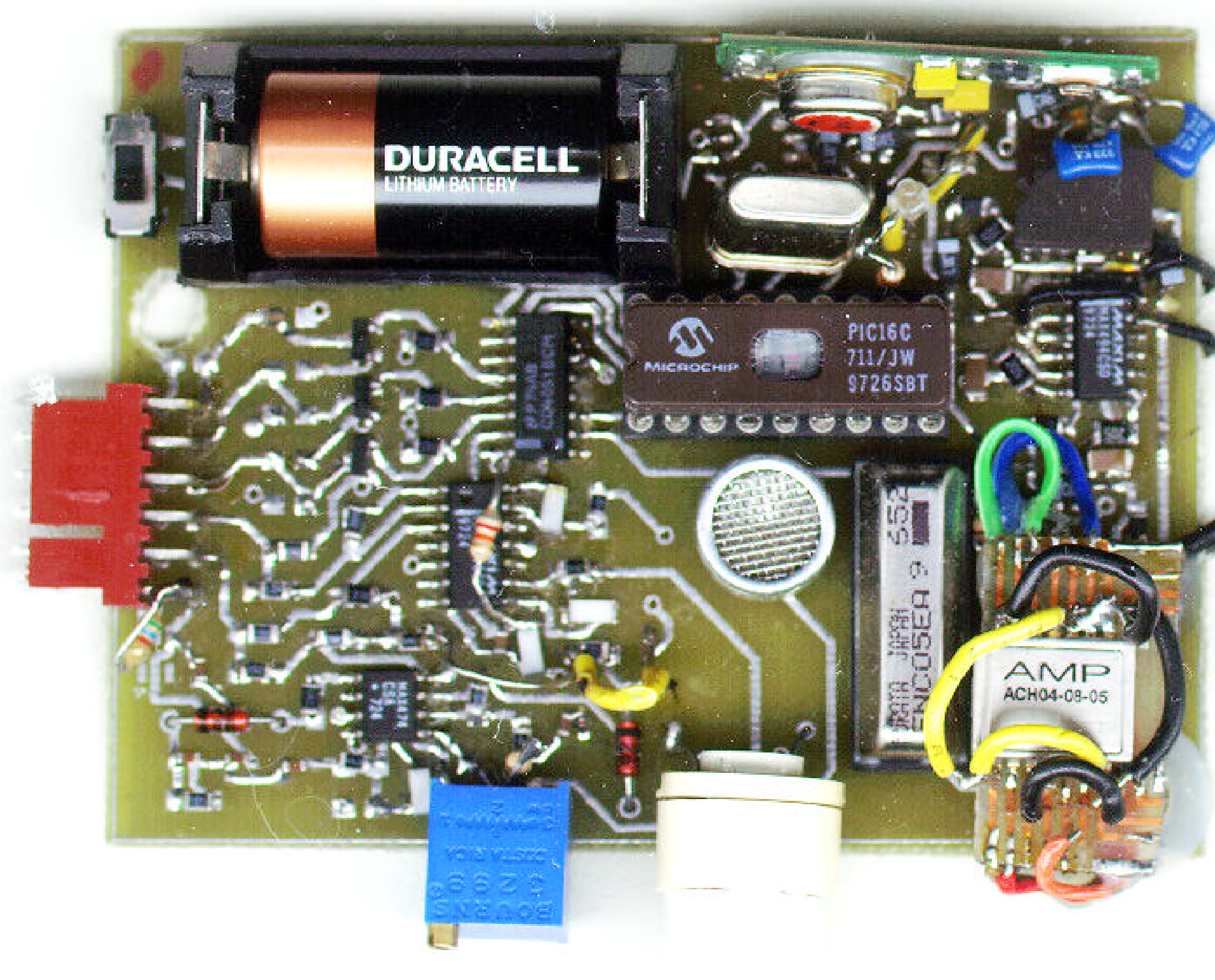


Figure 4: The original, working prototype of the shoe electronics card

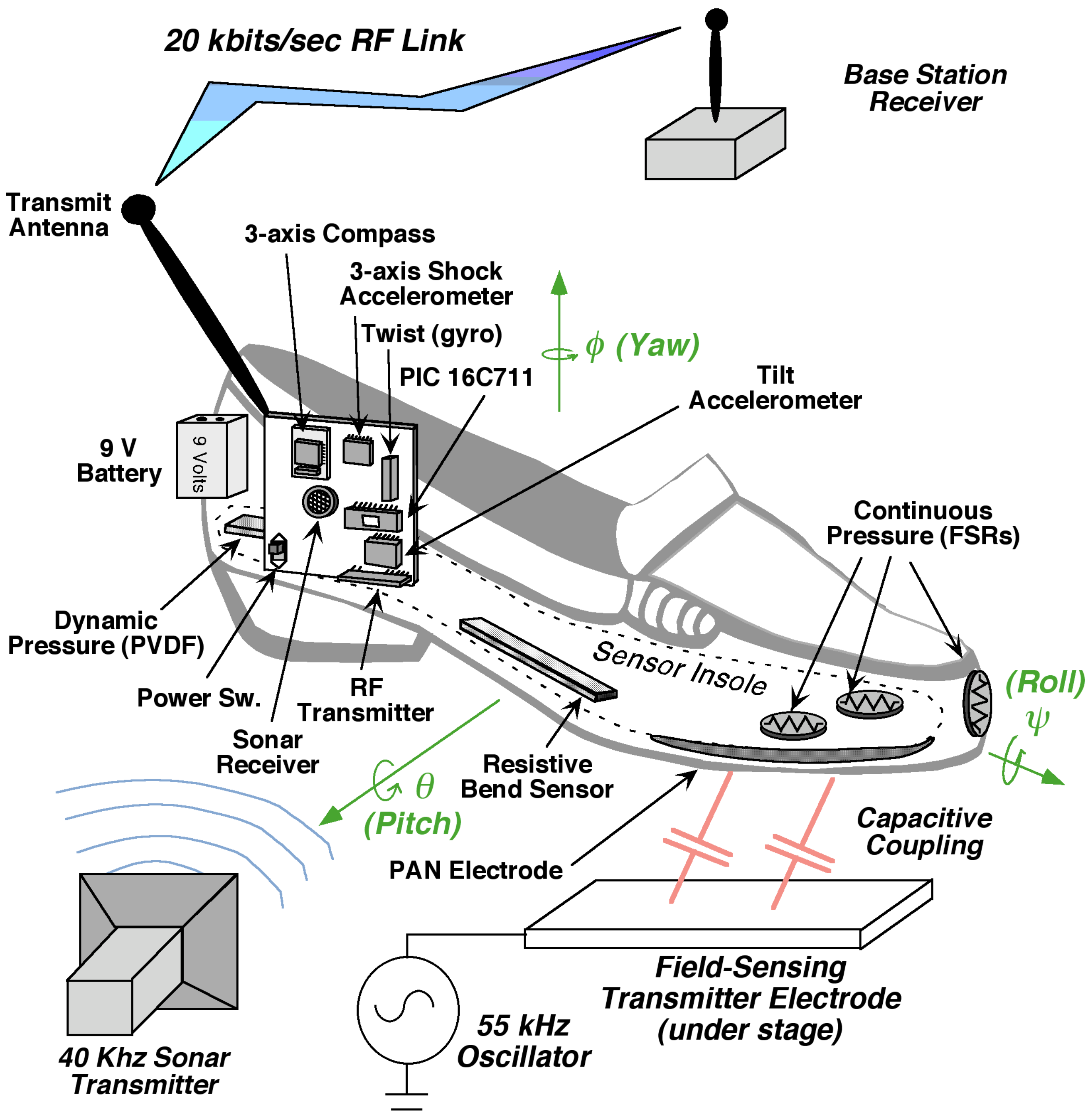


Figure 5: Block diagram of final shoe sensors and electronics

Figure 6: MIT student dancer Yuying Chen demonstrating prototype shoes at the 1997 Wearable Computing Fashion Show

Figure 7: The most recent pair of instrumented shoes

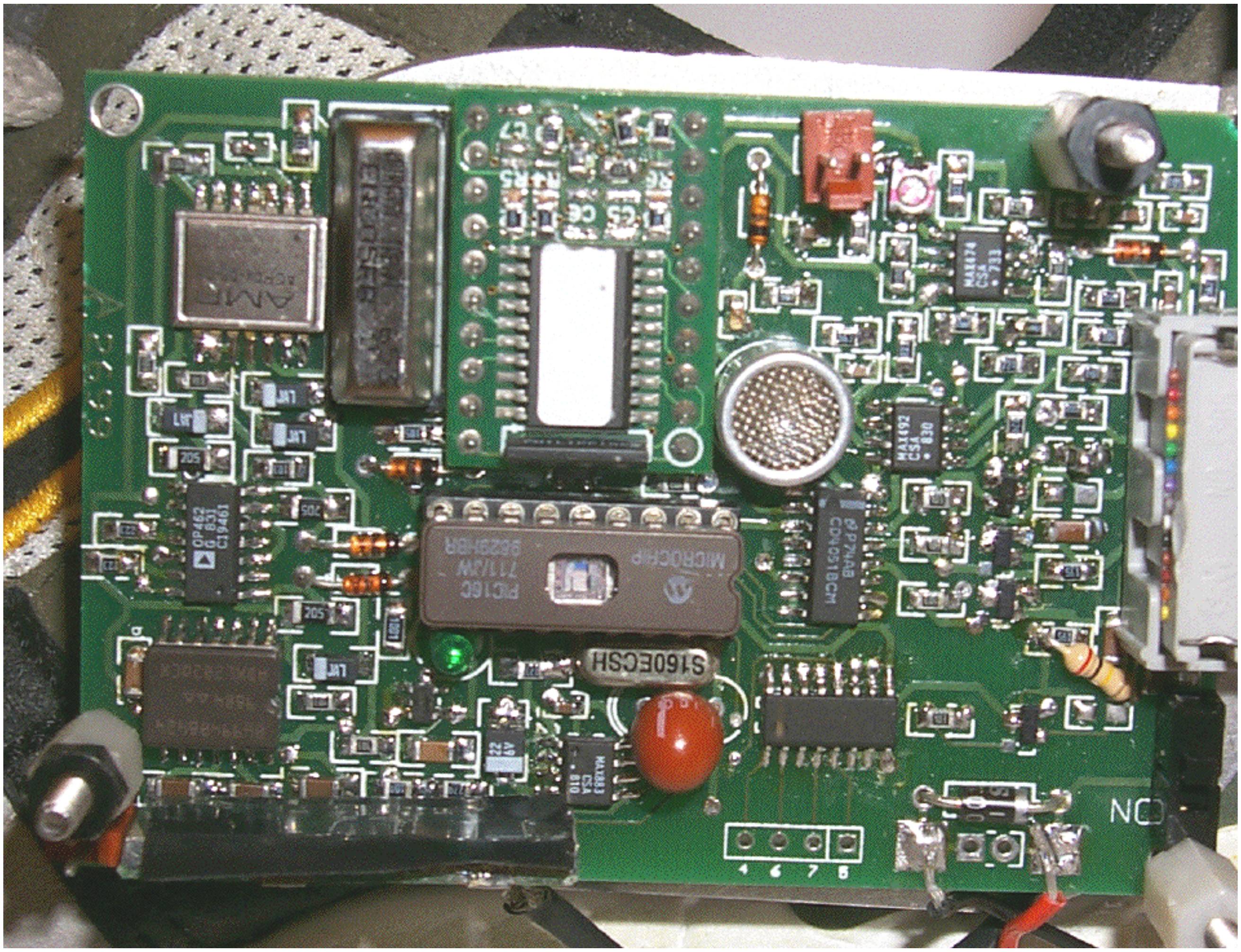


Figure 8: A close-up of the most recent electronics card

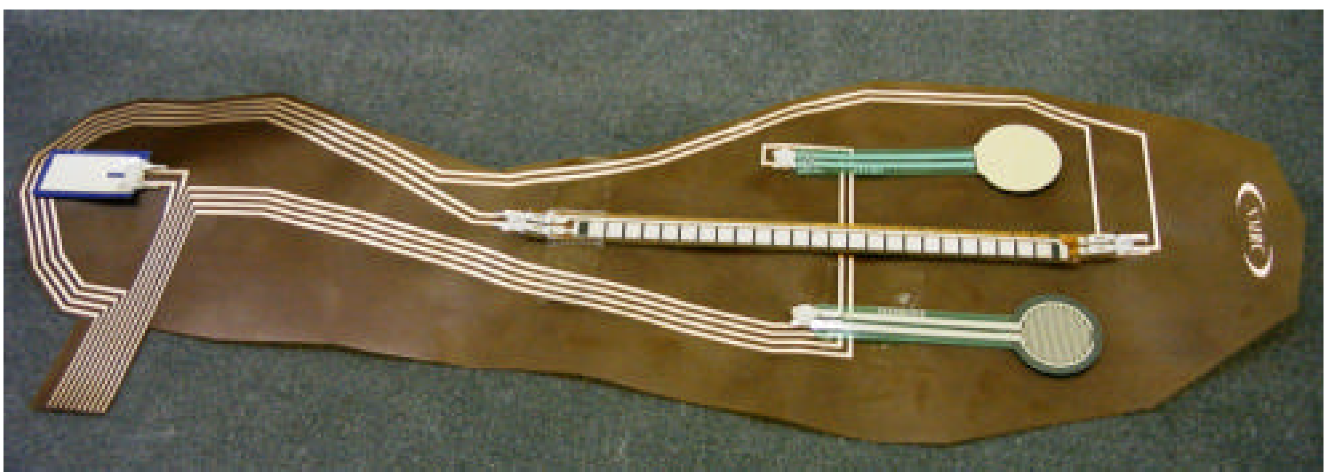
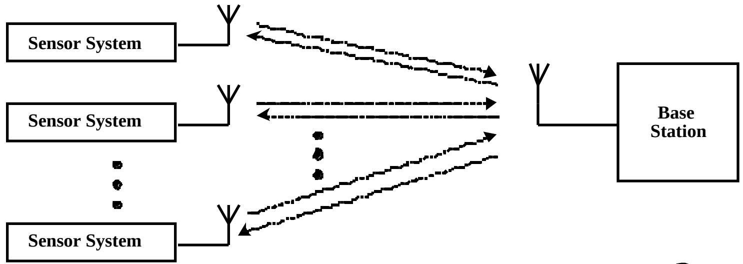
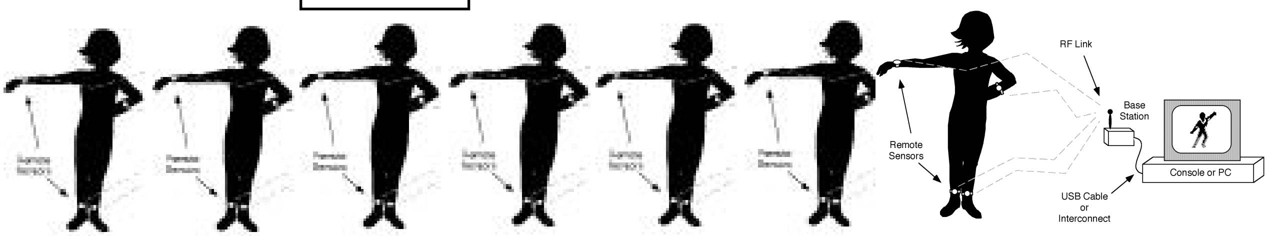


Figure 9: The new sensor insoles based on flexible printed circuitry, built by NMRC in Ireland

Figure 10: The Shoes in performance: at the 1997 Wearables Fashion Show (left), the 1999 American Dance Festival (right), the 1999 Tokyo Toy Fair (center) and the 2000 Discover Awards Ceremony (top & bottom)

Need for simple, lightweight networks for artistic performance





More sensor arrays...

– Equip entire ensemble (upper and lower limbs)
– Move to low-power channel-shared (TDMA) transmitter
  - Simpler than Bluetooth - more nodes, less protocol

Collaboration with Charlie Sodini and MTL

Figure 11: A wirelessly networked interactive dance ensemble