The CyberShoe: A Wireless Multisensor Interface for a Dancer's Feet

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Abstract: As a bridge between our interest in Wearable Computer systems and new performance interfaces for digital music, we have built a highly instrumented pair of sneakers for interactive dance. These shoes each measure 16 different, continuous parameters expressed by each foot and are able to transmit them wirelessly to a base station placed well over 30 meters away, updating all values up to 60 times per second. This paper describes our system, illustrates its performance, and outlines a few musical mappings that we have created for demonstrations in computer-augmented dance.

Electronic sensors have been incorporated into footwear for several different applications over the last several years. Employing force-sensing resistor arrays or pixelated capacitive sensing, insoles with very dense pressure sampling have been developed for research at the laboratories of footwear manufacturers and pediatric treatment facilities (Cavanaugh, *et. al.*, 1992). Although these systems are generally hardwired to a stationary basestation, portable insole systems with lower-density sensor arrays (e.g., *www.clevemed.com*) are now beginning to appear for rehabilitative treatment or prevention of foot injury when the patient exhibits a potentially injury-prone condition such as neuropathy. As sensors and associated processing systems decrease in cost and bulk, they also begin to adorn athletic footwear. Examples are a pressure-sensing insole for golfers to improve their balance during a swing (*www.pro-balance.com*) and inertial sensors (accelerometers and/or gyros) to perform pedometry measurements in jogging shoes (Hutchings, 1998). Although most interfaces for virtual reality applications concentrate on the hands, fingers, and head, some have been extended to the feet. Examples are NCSA's CyberBoots (Choi and Ricci, 1997), which used an array of pressure sensors mounted in an overshoe to drive interaction when walking in CAVE (Cave Automatic Virtual Reality Environment) installations, and the "Fantastic Phantom Slipper" (Shirai, *et. al.*, 1998), where a pair of infrared-emitting shoes are tracked over a limited area and haptic feedback applied by driving vibrators in the sole.

For the most part, sensing in dance footwear has been limited to simple pressure measurements. Examples are found in wireless electronic tap shoes (di Perna, 1988) and in the footwear of electronic bodysuits, such as the Yamaha Miburi (Paradiso 1997), which has a piezoelectric pickup mounted in the toe and heel of each shoe. These sensors are not stand-alone, but are generally wired to a central (e.g., beltpack) transmitter via cables running up the dancer's legs.

The goal of our system was to make many different kinds of measurements at a dancer's foot (e.g., pressures, positions, angles, inertial quantities), and transmit the data continually to a base station, directly from each shoe. By measuring many different kinds of dynamic parameters, we capture much of the expression that trained dancers can evoke at their feet. By mounting all required sensors, circuitry, batteries, and transmitters directly on the shoe, there are no constricting cables or tethers involved. Our applications thusfar have explored possibilities between interactive music and improvisational dance, where the wealth of sensor data streaming from a dancer's feet is interpreted in a computer and used to launch and modify synthesized notes, timbres, and events.

• Shoe-Mounted Sensors and Electronics

Our initial concept was described in (Paradiso and Hu, 1997), and the shoe systems that were actually built were introduced in (Paradiso, Hu, Hsiao, 1998). Fig. 1 shows the physical layout of our current shoe system, including all sensors, while Fig. 2 is an actual photograph of one of our operational shoes. A Lucite cover, omitted in Fig. 2, protects the electronics from accidental damage through inadvertent impacts.

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Although we originally built our electronics onto a Capezio “Dansneaker”, we have subsequently moved to a Nike Air Terra Kimbia, better matching the costumes designed by our choreography collaborators. The only components inside the shoe are pickup and grounding electrodes sandwiching a set of pressure and bend sensors embedded in a “Dr. Scholl” foam insole inserted between the sole of the shoe and the sneaker’s insole (the dancer is unable to feel any wires or sensors through this). As depicted in Fig. 1, all other sensors and electronics are mounted on a small circuit card affixed to the outer side of the shoe. Although this does somewhat constrain the freedom of foot motion, it is a compromise solution that interferes minimally with the dancer's movements. With additional design effort, the electronics package can become less cumbersome and better integrated to the shoe.

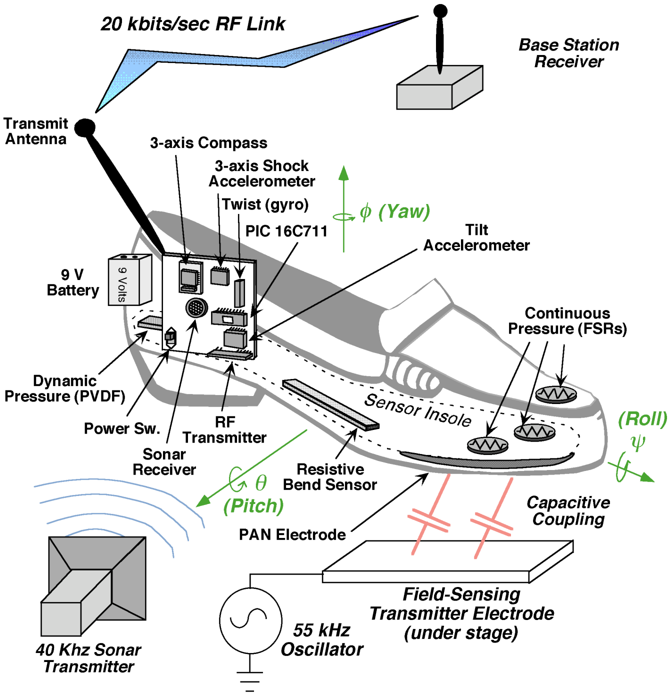

Figure 1: Diagram of the instrumented shoe

Figure 2: Photograph of the shoe and electronics

All sensors are labeled in Fig. 1. Force-sensitive resistors are used to measure continuous pressure at two points under the toes and at one point above them (engaged when pointing). Dynamic pressure is measured at one point under the heel by a piezoelectric film (PVDF) strip (Paradiso 1996). The bidirectional bend of the sole is measured by a pair of back-to-back resistive bend sensors, such as are commonly used to monitor fingers in glove interfaces. These sensors are mounted off the electronics card;

all are in the foam insole (dotted line in Fig. 1) except for the upward-pressure toe sensor, which is inserted between fabric layers at the toe.

When the shoe isn't quickly jerked, the tilts in pitch (θ) and unsigned roll (ψ) are measured by the ADXL202, a low-power, dual-axis, low-G, micromechanical accelerometer from Analog Devices. Large impacts and fast kicks are detected by a 3-axis, high-G piezoelectric accelerometer from AMP Sensors. The 3-axis angular orientation (including twist [φ]) is inferred by a 3-axis, solid-state magnetic sensor hybrid made by Honeywell (the HMC2003). In venues where the Earth's magnetic field is relatively stable (e.g., not distorted by large amounts of ferrous metal), this compass can indeed determine the orientation of the foot; otherwise the absolute accuracy is compromised, but it nonetheless responds well to changes in the foot's angular position. Another sensor, a Murata vibrating-reed gyroscope, is dedicated to measuring angular rate in φ, e.g., the speed of twisting about the vertical. A 1-cm diameter, 40 kHz piezoceramic transducer from Polaroid receives sonar pings from transmitters scattered about the stage, allowing the translational foot position to be determined by time-of-flight measurements. The bottom of the sensor insole is covered by an electric-field-sensing (Paradiso 1997) receive electrode, labeled "PAN" (Zimmerman 1996) in Fig. 1, which is tuned to detect signals transmit from conductive strips placed beneath or atop the stage. As the strength of this signal varies with the capacitive coupling into the shoe (hence distance from the transmitting electrode), it reflects the height of the shoe atop these transmitting zones in the stage.

All signals are digitized by an onboard PIC16C711 microcomputer running at 16 MHz. A zero-balanced data stream is generated, and broadcast to a base station located at a maximum distance of 30 to 200 meters from the dancer (depending on the local RF environment) by a small FM transmitter, a TXM series device from Abacom Technologies (Eady, 1998). As these devices are able to transmit at up to 20 Kbits/sec, we can refresh all parameters at 60 Hz; with a more elegant zero-balancing algorithm (we currently use a simple Manchester Code), we can approach the vicinity of 100 Hz. Each shoe broadcasts continually at a different frequency (currently 418 and 433 MHz) through a stub antenna; for shorter ranges, this can be replaced by a quarter-wavelength of wire (roughly 18 cm) affixed to the shoe. Although our earlier versions of the electronics included space for a small ($^1/_2$ AA) 6-Volt lithium camera battery on the electronics card, we have moved to a 9 Volt battery, separately mounted near the heel. As the maximum current drain is 50 mA, the camera battery already allowed us to reach roughly 2-3 hours of useful battery life; the 9 Volt battery provides many additional hours, sufficient for several performance and practice sessions (the shoes have an off switch to enable batteries to be conserved). The shoes send two battery status indicators across the uplink. One is a digitization of an internal 3-volt supply relative to the 5-volt PIC reference and the other is a binary flag that is set when the battery needs replacing. Abrupt changes in the 3-volt parameter signify trouble with the shoe electronics or RF link, while its continuous value indicates the rate at which the batteries are drained, allowing compensation of nonratiometric sensor outputs.

A pair of base stations receive the RF telemetry stream from each shoe and send the data on to a host PC (running the musical mappings and controlling MIDI synthesizers) over an RS232 serial line. One of the base stations also handles the sonar transmitters; up to four sonar sites (at different stage locations, if desired) can be pinged in any combination.

• Sensor Performance

Fig. 5 shows a 12-second snippet of data taken while the shoe of Fig. 2 was worn. The top-left pair of signals show the continuous pressure measured at the toes. Here, one sees considerable structure associated with footsteps at the beginning and end of this data. In the middle of this test, the pressure data is much less active, as the shoe was elevated off the floor here and freely articulated. The dynamic heel pressure shows a similar profile (note that the PVDF strip measures pressure transients here, not continuous pressure, thus is much more "spiky" in appearance), as does the sole bend (this Nike's sole is much stiffer than that of the Capezio used in the original prototype, and doesn't easily bend backwards). The footsteps and foot elevation are also seen very clearly in the electric field ("PAN") height data. The forward and side tilt accelerometer signals measure the pitch and roll of the shoe, but also respond to transients from footsteps and kicks, giving the visible spikes, which can be filtered out by the host computer. The twist gyro picks up fast yaw dynamics (although the dancer wasn't twisting rapidly during this data segment), and the magnetic sensor ("compass") signals respond well to the foot's angular articulation. The shock accelerometers clearly show the jumps at the beginning of the test, also seen in the PAN sensor's height data. As we are now developing revised sonar code for the onboard PIC, ranging data is not included in Figure 3. In earlier tests, however, we have used the sonar successfully, measuring range out to 30 feet when projecting from a fan-array of simple 40 kHz Murata PZT ultrasound drivers, attaining a resolution of circa 6 inches, limited mainly by the PIC's timing algorithm and the effects of background noise. We anticipate that this sonar will perform adequately for lower-bandwidth control; e.g., switching modes as the dancer moves into different regions of the stage.

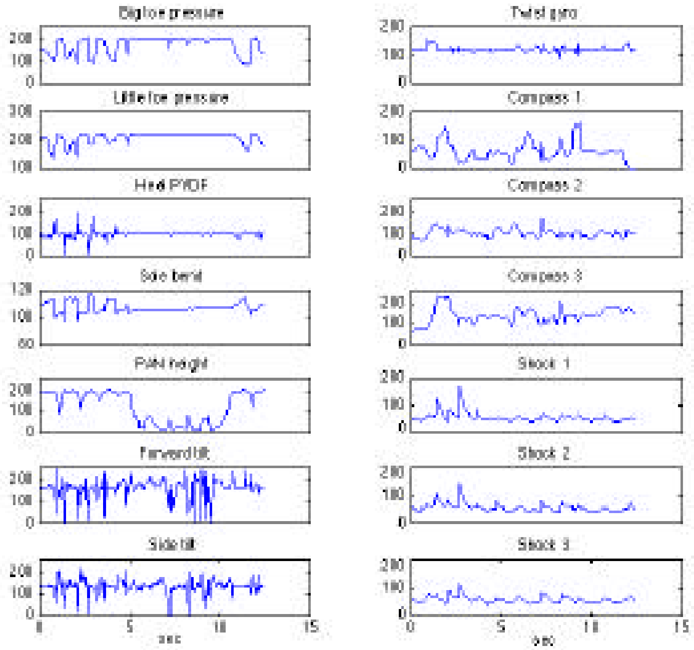

Figure 3: Sample data taken with the CyberShoe

Figure 4: Shoes in performance at MIT Wearables Show

- Dance Applications

In order to evaluate our prototype hardware, we have written a couple of software application to map the data from the shoes onto a simple musical structure. All of these were written in ROGUS (Denckla, 1996), a set of C++ libraries that handle MIDI functions, and ran on a standard PC. The first was designed for the Wearable Computing Fashion Show (Judge 1997) held at the MIT Media Laboratory in October of 1997 (see the first video clip). As it was intended for a brief on-stage walkthrough, the mapping was very simple and literal; easily mastered, although very limited in scope. Also, as only one early-prototype shoe was totally functional at that time, this mapping was designed to work with only a single shoe. The music itself consisted of three voices: a drum voice, a bass voice, and a melody voice. The drum voice ran steadily throughout the whole piece and gave a rough “techno” feel to the music, fitting the mood of the fashion show. The volume of the bass drum and the bass voice were controlled by the θ tilt accelerometer, and the volume of the other drum instruments was controlled by the electric field height sensor. The tempo was adjusted slightly by the bend sensor. The bass voice and melody voice were switched on and off in various combinations as impulses were detected by the high-G accelerometer. The bass voice itself produced a harmony effect, and the specific harmony was selected by rotating the shoe in φ. The bass voice was articulated by changing its octave upon detecting impulses from the rear piezo sensor. The melody voice played harmonizing melody tones in upper registers; the range of the melody voice was controlled by the front pressure sensors. Panning and flanging of both voices were controlled by the detected compass direction. Also attached to the high-G accelerometer was an explosion sound, which triggered with heavy stomps and kicks. Finally, a panning wind sound was produced with quick φ rotations, as detected by the twist gyro. An MIT student dancer (Yuying Chen) practiced with these mappings, and performed at the Fashion Show (Fig. 4); the second video clip shows a short excerpt of her demonstrating aspects of this mapping algorithm.

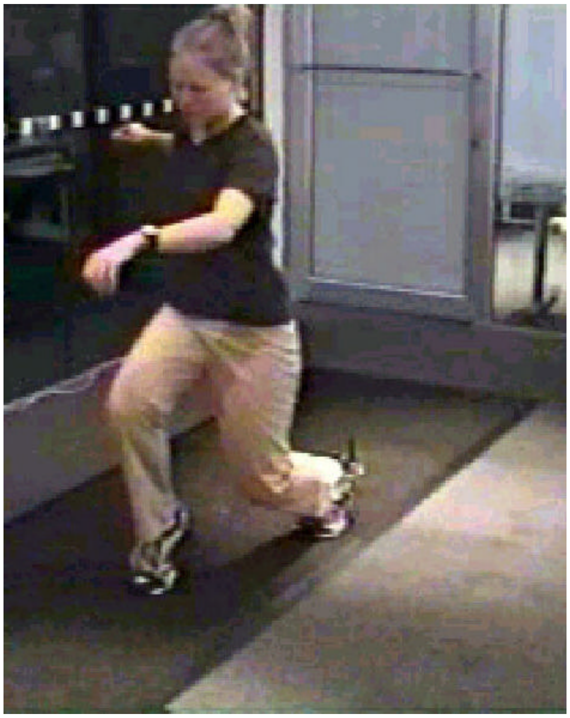

Figure 5: Dance improvisation on a pair of CyberShoes

The third video clip shows a more recent musical mapping that we have written to demonstrate a pair of operational performance shoes of the kind shown in Fig. 2. This mapping has no pedestrian rhythm, but is entirely freeform, triggering and modifying simple sounds in accordance with the dancer's gesture. We tied random melodic notes to toe and heel pressure, and the bend of the sole selected a harmony chord that was changed in volume in accordance with the pitch tilt (θ) of the shoe; roll tilt (φ) faded up an additional harmony chord. The height of the shoe above an electric field transmitter embedded in the carpet dictated the volume of the bass pedalpoint notes (they increased in volume as the shoe approached the floor). A fast movement or stomp, as detected by the high-G accelerometers, introduced percussive sounds, and fast twists, as indicated by the rate gyro, introduced a stream of random piano notes. Since the Earth's magnetic field was too well-shielded in this portion of the Media Lab building, no compass mappings were used. Likewise, as the related embedded software is currently being revised, this example did not use the sonars. Our performer here (Fig. 5) was another MIT dancer, this time Mia Keinanen from the Media Lab's Gesture and Narrative Language Group.

In another project using the prototype shoes (*www.media.mit.edu/~mkgray/research/Fall97.html*), real-time classification algorithms have been developed that detect certain dance styles from the shoe data stream; e.g., discriminating between a waltz and a tango. After exposing the analysis to several seconds of the real-time dance data, the appropriate musical accompaniment would fade up once the decision was completed.

• Next Steps

The hardware development is nearly completed; all sensors are working and integration of the sonar algorithms is now concluding. Future work will concentrate on applications of our shoe system. Note that both shoes together will produce 32 parameters of useful gesture information, hence the task of mapping these onto musically relevant and choreographically interesting events is a challenging one, which we are now embarking upon in collaboration with colleagues who work in both dance and composition. These shoes likewise produce a wealth of data on human gait, which enable us to explore applications in other areas, such as sports and rehabilitative medicine. The highly-integrated, wireless sensor card that we have developed can be readily used in other areas; e.g., it can be worn on other parts of the body (i.e., arms, head) or embedded into smart objects used in conjunction with a performance. We have already begun examining some of these possibilities (Blumberg, *et. al.* 1998). As these wireless interface devices proliferate and begin to interfere with each other's data transmissions, an acute need for very low-power, minimal-overhead, moderate-bandwidth channel-sharing quickly arises. We are currently researching available spread-spectrum transmitters to replace the fixed frequency FM transmitters used with the current device.

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