# Instrumented Footwear for Interactive Dance


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## ABSTRACT

We have instrumented a dance sneaker with an array of sensors that measure many parameters of foot, sole, and toe expression, continuously broadcasting them to a base-station and PC over a wireless link. This paper describes this system, reports its performance and outlines applications that we have developed for it in the field of interactive dance.


## INTRODUCTION

Because of the comparatively high degree of manual dexterity in the general population, most human-computer and musical interfaces concentrate on precisely measuring gesture expressed by the hands and fingers, devoting little, if any, attention to the expressive capability of the feet. We have developed an interface that breaks this tradition by measuring many parameters that can be articulated at the foot of a trained dancer. Previous foot-sensing performance interfaces have generally been very simple, measuring only impacts at the heel and toe, usually with a piezoelectric pickup. Some of these were standalone shoes built for custom performances [1], while others, such as the Yamaha Miburi [2] are components of larger body-suit systems. Instrumented footwear has started to appear in virtual reality (VR) installations, for instance in the "Cyberboot" [3], an overshoe equipped with continuous pressure sensors to capture the dynamics of walking in CAVE (Cave Automatic Virtual Reality Environment) installations. Another foot interface for VR systems is the "Fantastic Phantom Slipper" [4], which uses an IR LED and PSD camera to track the position of feet atop a floor-mounted projection screen; here haptic feedback can also be generated by driving vibrators in the sole. Foot sensing has appeared in other application domains, such as in the research and development laboratories of major footwear manufacturers and biomechanical researchers, where detailed pressure profiles are obtained across the sole [5]. Although they collect fine-grained data, these interfaces are usually bulky, expensive and hardwired, inhibiting their application in areas such as dance. Some designers are beginning to deploy miniature inertial sensors in footwear for pedometry [6], producing jogging shoes that measure elapsed distance.

Our system, proposed initially in [7], was designed to go well beyond the simple tap detectors, pressure sensors, or pedometers sketched above and sense many of the different degrees of freedom that could be expressed at a dancer's foot. The system is entirely tetherless and self-contained; everything, including a small lithium battery that provides circa 3 hours of power, is mounted on the shoe, and data is offloaded from each foot over a wireless link.

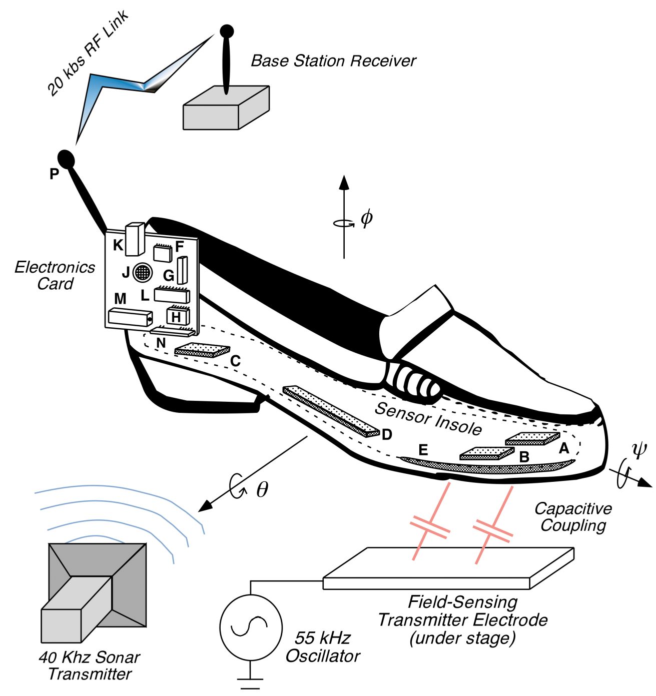


Figure 1: Diagram of the instrumented prototype shoe

## THE PROTOTYPE SENSOR SUITE

Figure 1 shows the physical layout of our prototype system, including all sensors, while Figure 2 is an actual photograph of one of our early operational prototype shoes. We chose a Capezio "Dansneaker", which gave us sufficient room to mount our electronics without prohibitively impacting the dancer's movement. The only components inside the shoe are a set of tactile sensors and electrodes embedded in a standard "Dr. Scholl" foam insole sandwiched between the sole of the shoe and the sneaker's insole (the dancer is unable to feel any wires or objects through this). All other sensors and electronics are mounted on a small circuit card affixed to the outer side of the shoe, where it interferes minimally with the dancer's movements. In total, the prototype shoe measured 14 different parameters per foot, as described below.

The dynamic foot pressure is measured at two points under the toes (A,B) and one point at the heel (C) by piezoelectric film (PVDF) strips [8] mounted in the insole, as seen in Fig. 1. The bidirectional bend of the sole (Dansneakers are designed to allow large amounts of flex) is measured by a pair of back-to-back resistive bend sensors (D). When the shoe isn't quickly jerked, the two-axis tilt in pitch ($\theta$) and roll ($\psi$) is measured by a 2-axis, 2G ADXL202 micromechanicalaccelerometer from Analog Devices (H). Large impacts and fast kicks


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Figure 2: Photograph of the prototype sensor Dansneaker

are detected by a 3-axis, high-G ACH-04-08-05 piezoelectric accelerometer from AMP Sensors (F). In our prototype system, the twist angle (φ) was inferred when the foot is nearly level by an electromechanical compass made by the Dinsmore Co. (K), and the angular rate in φ determined by a small Murata Gyrostar vibrating-reed gyroscope (G). A 1-cm diameter, 40 kHz piezoceramic transducer from Polaroid (J) 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[9] receive electrode (E), which is tuned to detect low-level, 60 kHz radio signals transmit from conductive strips placed beneath 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 shoe's height atop the transmitting zones in the stage.

All signals are digitized by an onboard 16-MHz PIC16C711 microcomputer (L) that converts analog data into 8 bits and times the sonar and ADXL202 signals. A zero-balanced data stream is generated and broadcast to a base station up to 200 meters away by a small FM transmitter (N), a TXM series device from Abacom Technologies [10] transmitting at 19.2 Kbits/sec. Our current embedded software updates all parameters at 25 Hz, which is conservative; when running at the maximum data throughput, we anticipate the performance system to be able to refresh all parameters at 50 Hz. Each shoe broadcasts continually at a different frequency (currently 418 and 433 MHz) through a stub antenna (P) and is powered by a small ($^1/_2$ AA) lithium 6-Volt camera battery (M). As the maximum current drain is 50 mA, these cells allow us to reach roughly 2-3 hours of useful battery life, sufficient for most performances (the shoes have an off switch to enable batteries to be conserved and send a binary battery status indicator across the RF uplink).

## DANCE APPLICATIONS OF THE PROTOTYPE

In order to evaluate our prototype hardware, we have written a software application to map the data from a shoe onto a simple musical structure. This initial mapping was chosen to be extremely literal, enabling an improvisational dancer to quickly exploit such a novel interface. The music itself consisted of three voices: a drum voice, a bass voice, and a melody voice, articulated and controlled by a single shoe as outlined below.

Figure 3: Shoes in performance at MIT Wearables Conference

The drum voice ran steadily throughout the whole piece and gave a rough "techno" feel to the music. The volume of the bass drum and the bass voice were controlled by the θ tilt sensor, and the volume of the other drum instruments was controlled by the electric field sensor. The tempo was adjusted slightly by the bend sensor. The bass voice and melody voice were switched on and off in various combinations by the hi-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 based on input from the heel piezo sensor. The melody voice played harmonizing melody tones in upper registers; the range of the melody voice was controlled by the front piezos. Panning of both voices were controlled by the compass direction. Also attached to the hi-G accelerometer was

Figure 4: Photograph of the performance test design

an explosion sound, which triggered on heavy stomps and kicks. Finally, a panning wind sound was produced with quick φ rotations. A dancer practiced with these mappings, and performed [11] in the Wearables Fashion Show at the Media Lab in October 1997 (Fig. 3).

In another project [12], we have developed real-time classification algorithms that detect certain dance styles from the shoe data stream; e.g., discriminating between a waltz and a tango.

## THE PERFORMANCE SHOE

After working with the prototype shoe for a few months, we modified and perfected our design to produce a shoe that will be robust enough for use in a professional dance performance. The sensor suite is identical, except that we have replaced the 2-axis electromechanical compass (which exhibited poor bandwidth and didn't hold up well enough to the shock and kinetics at the dancer's foot) with a solid-state, 3-axis magnetic field sensor from Honeywell (the HMC2003). Although these permalloy bridges can magnetize and drift over time, we have found them to be stable across several days after applying a single reset pulse to the device's common magnetizing strap, which we have made available at a connector on the edge of the card. We have also substituted force-sensitive resistors (FSR's), which provide continuous pressure readings, for the two PVDF strips at the toe, and added an additional FSR pressure sensor for measuring the pressure of the toes against the top of the shoe. We now measure an internal 3-Volt reference with the PIC A/D converter (which runs off the 5-Volt supply), giving a continuous indication of the battery state. These additions now bring the total number of transmitted analog channels to 17.

Fig. 4 shows the performance sensor card temporarily mounted onto a Nike "Air Terra Kimbia" sneaker, chosen by our collaborating choreographer for an upcoming performance. In our latest design, we have opted not to mount the battery on the circuit board, allowing greater application flexibility and freeing up layout space. We are now designing a robust, plastic, 3D-printed case to enclose the sensor card, electronics, and 9V Lithium battery, which should provide for over a day of continuous operation.

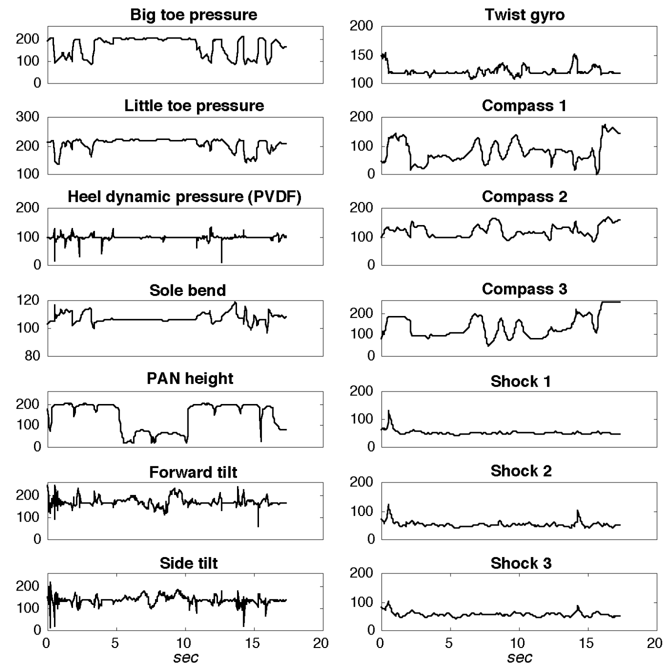


Figure 5: Actual data taken with the sensor shoe

Fig. 5 shows an 18-second snippet of data taken while the shoe of Fig. 4 was worn. The top-left pair of signals show the continuous pressure measured at the toes Here, one sees structure associated with footsteps at the beginning and end of the data; in the middle of the data stream 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), as does the sole bend (the Nike's sole is much stiffer than that of the Capezio used in the prototype). The footsteps and foot elevation are also seen very clearly in the electric field ("PAN" [13]) height data. The forward and side tilt accelerometer signals measure the pitch and roll of the shoe, as well as responding to transients from footsteps and kicks (giving the visible spikes). The twist gyro picks up fast yaw dynamics, and the magnetic sensor ("compass") signals respond well to attitude changes. The shock accelerometers are relatively quiet here, excepting at the beginning (when the user jumped) and at the end (another jump). As this run was taken in a small area, the sonar data is not shown. We have used the sonar successfully in larger volumes, however, measuring range out to 30 feet when using simple 40 kHz Murata PZT ultrasound drivers and 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).

## FUTURE WORK

We are now concentrating on completing the performance shoe system, and are planning to finish a pair shortly with full base station support and faster sampling. Both shoes together will produce 32 parameters of useful gesture information, and 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. The shoes produce a wealth of data on human gait, which likewise enable us to explore applications in other areas, such as sports and rehabilitative medicine.

The wireless sensor card that we have developed measures many general parameters, and is relevant to several applications beyond footwear. In this spirit, we have recently collaborated with our colleagues in the Synthetic Characters group at the MIT Media Lab to use our card in a multimodal interface recently shown at SIGGRAPH 98 [14]. Here, the card and an array of sensors were embedded in a stuffed toy "chicken"; by manipulating the toy, users were able to interact with similarly-appearing, semi-autonomous characters in an interactive animation.

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