Interfacing to the Foot: Apparatus and Applications

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ABSTRACT
We describe a system that we have developed to capture detailed, multimodal gesture expressed at the foot. It is embodied in a pair of shoes, each of which measures 16 degrees of freedom (tactile, inertial, positional). No tethers or wires are attached to the shoes; data is directly telemetered wirelessly off each foot to a remote base station and host computer, yielding full state updates at 50 Hz. This system, having evolved over 3 years, has been used for real-time expressive performance by a diverse set of artists, including gymnasts, jugglers, and dancers. Ongoing work is exploring the extraction of high-level podiatric gesture.

Keywords
Sensor shoes, wireless sensing, motion capture, body suit

INTRODUCTION
As an outgrowth of our interest in dense wireless sensing (e.g., sensing many degrees of freedom in a compact, telemetered package) and expressive applications of wearable computing, we have developed the world's most versatile human-computer interface for the foot. Previous work in this area has typically concentrated on only one mode of sensing per niche application. For instance, musical shoes have been instrumented only with piezoelectric taps at toe and heel, medical applications measured only pressure distributions, athletic footwear have recently began to introduce accelerometers for pedometry, and some VR installations have measured foot pressure and/or the shoe's translational position. Our work has broken these boundaries, measuring essentially all types of gesture that the can be expressed directly at the foot, without wires or tethers.

THE CYBERSHOE SYSTEM
Our "cybershoe", proposed originally in [1], has developed over a period of two years into the system [2] shown in Fig. 1 that we have used for interactive music applications with a variety of different performers. For each shoe, the hardware, detailed in [3], consists of a circuit card (mounted on the side of the shoe as shown with protective cover removed), antenna, sensor insole, and remote base station.

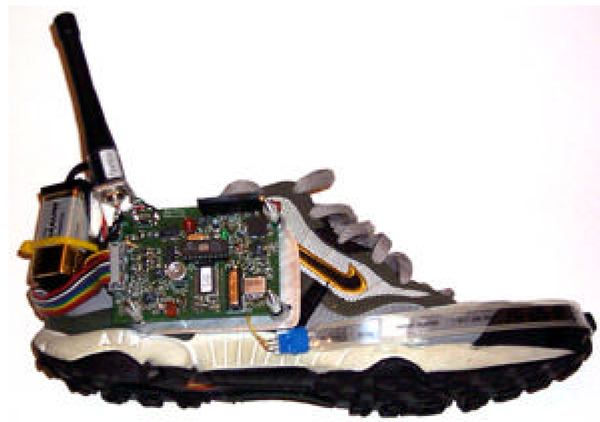

Figure 1: "Cybershoe", electronics card, and battery

The sensor insole contains two continuous pressure sensors (force-sensitive resistors [FSRs]) below the front toes (at left and right sides) and one encapsulated FSR is placed outside the shoe, directly in front of the toes, measuring pressure during pointing, when the shoe is oriented vertically. The insole also contains a strip of piezoelectric foil below the heel to measure dynamic pressure there, a bi-directional resistive bend sensor to determine the bend of the sole, and a tuned capacitive pickup electrode. When a shoe is above a region of the stage covered with a transmit electrode (a sheet of foil or screen connected to a low-voltage 50 kHz oscillator), the magnitude of the voltage measured at the shoe-mounted pickup electrode corresponds to the height of the shoe above the stage.

The circuit card contains a variety of inertial and positional sensors, in addition to the host microcomputer and RF transmitter. A miniature, vibrating-reed rate gyro is aligned with the ankle, thereby directly measuring spins. A 3-axis solid-state magnetometer (e.g., compass) measures the angle of the shoe with respect to the local ambient magnetic field. A 2-axis, 2G silicon MEMs accelerometer measures tilt of the shoe with respect to the gravity vector and responds to foot swings. A 3-axis, high-G, piezoelectric accelerometer measures directional impacts, jumps, and fast kicks.

Each shoe card also contains a 40 kHz piezoelectric sonar receiver. Pings are periodically (every 100 msec) sent from up to 4 fixed stage locations by one of the base stations. The shoes measure the latency between receipt of a ping and transmission of the sonar data byte (the shoes have no RF receiver for synchronization). The base station measures the time between its pinging and the receipt of the sonar byte. The difference between the base station's time measurement and the latency sent by the shoe give the distance of the shoe from the sonar head. Under good conditions, our sonar system is able to resolve better than 6 inches and measure out to 20 feet; by combining the

MIT Wearables 97 Dancer | NICOGRAPH 98 Gymnast | Tokyo Toy Fair 99 Juggler | ADF 99 Byron Suber | SENS@BLES 99 Mark Haim

Figure 2: Several different types of performers using the sensor shoe system

readings from multiple pinger heads, the shoes can be tracked around the stage.

A PIC16C711 serializes and zero-balances the data by sending each data byte with its compliment. The base station compares the two bytes, declaring a transmission error if they don't agree. Using TX-series transmitters from Radiometrix Ltd, we are able to update all 16 states from each shoe at a 50 Hz rate. The dancer's telemetry is received up to 100 feet from the base stations, and the 9-Volt battery on each shoe lasts for a half-day of continuous operation. Currently, each shoe streams data at a fixed frequency (418 and 433 MHz). We are currently examining evolving channel-sharing schemes for a more efficient RF solution that will enable simultaneous operation of multiple sensor packages. Each base station now sends a serial stream to a PC, which runs higher-level gesture recognition and musical mapping algorithms.

APPLICATIONS

We have used this system with many different performers, as seen in Fig. 2. Our debut, at the Media Lab's Wearable Computing Fashion Show, used only one active shoe, which fired notes and embellished a background musical sequence as the dancer moved. We then used the full-up dual-shoe system to work with a gymnast, launching sonic events with detected twists, leaps, and handstands. We also worked with a juggler, who used the shoes to produce sounds to accompany his routine. Work with choreographer Byron Suber (Cornell University), culminated in performances at the American Dance Festival last July (2 dancers, with one shoe each) and improvisations with New York dancer Mark Haim last October. These projects used a very complicated mapping [2], where notes and musical samples were fired with toe/heel pressure, jumps, and twists, transposed with sole bend, then mapped and modified in many ways with position, height and angle. Clips of all of our performances are posted at: *http://www.media.mit.edu/resenv/danceshoe.html*.

CONCLUSIONS

Dancers and audiences responded very positively to this system, as the connection between sound and action was immediate and deliberate; our mappings sonically followed the performer's activity. Putting such control at the feet, however, required all primary dance gestures to involve the legs, modifying the dancing style (most interactive dance systems, which use video tracking, concentrate on the upper body). Although this took some adaptation, all dancers were able to appropriately rebalance their gestures. Our best results have been in working with skilled improvisational dancers who are also musicians, as this interface blends both composition and choreography.

The sensor suite produced a very rich stream of data that reliably monitored the dancer's activity. Although some of the sensor systems gave redundant information for many gestures, having access to such a multimodal description was invaluable for reliably detecting particular gestures. Our current mappings are primarily "direct manipulation"; sounds are tied to relatively simple gestures and postures, and the performer sculpts the composition by sequencing their movements appropriately. We are now looking at more sophisticated analysis to detect higher-level gesture, of particular use in dance and athletic training, performance monitoring, and medical podiatry.

The truly wireless nature of this package was a real win; dancers had only to lace up the shoes, and flip the power switch to use the system. Although the antenna was slightly cumbersome, performers had little difficulty with the side-mounted card, and in their final design iteration, the shoes were highly reliable. With additional design refinement, the circuitry can be further miniaturized or integrated into the shoe itself (and the antenna shrinks with higher frequency), making the device totally unobtrusive.

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