Design and implementation of Expressive Footwear

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As an outgrowth of our interest in dense wireless sensing and expressive applications of wearable computing, the Responsive Environments Group at the MIT Media Laboratory has developed a very versatile human-computer interface for the foot. By dense wireless sensing, we mean the remote acquisition of many different parameters with a compact, autonomous sensor cluster. We have developed such a low-power sensor card to measure over 16 continuous quantities and transmit them wirelessly to a remote base station, updating all variables at 50 Hz. We have integrated a pair of these devices onto the feet of dancers and athletes, measuring continuous pressure at three points near the toe, dynamic pressure at the heel, bidirectional bend of the sole, height of each foot off conducting strips in the stage, angular rate of each foot about the vertical, angular position of each foot about the Earth's local magnetic field, as well as foot tilt and acceleration, 3-axis shock acceleration (from kicks and jumps), and position (via an integrated sonar). This paper describes the sensor and electronics systems, then outlines several projects in which we have applied these shoes for interactive dance and the capture of high-level podiatric gesture. We conclude by outlining several applications of our sensor system, which are unrelated to footwear.

Wearable technology has long had application in musical expression. A historical example can be seen in the "one-man-band,"[1] a concept that dates back well over a century, long before the dawn of electronics. Figure 1 shows a modern incarnation in such a rig, with each "instrument" mounted for convenient access, responding to the action of a particular limb or a specific, controllable motion of the wearer. Since the instruments were traditionally acoustic, each made a particular kind of sound, and the "action-to-audio" mapping was essentially static. In order to attain a timbral richness approaching that of a "band," many such instruments were scattered about the body. Despite the apparent clutter, performers could use these adornments to charm and amuse audiences with occasionally virtuosic (although often acrobatic) musical expression as they appropriately flailed away.

With the dawn of electronics, the situation evolved. Now the instruments themselves did not have to be mounted on the performer's body, since they could be replaced by a set of electronic sensors that picked up the motion cues and controlled a remote music synthesizer. In the 1980s, the MIDI (Musical Instrument Digital Interface) standard and digital synthesis brought these systems even further, since now a computer could be easily placed in the loop, recognizing particular motions from real-time analysis of the sensor signals and producing a more complex, dynamic, and captivating software mapping of sound onto action. This was a very liberating process, because the sensor systems freed the body from bearing the burden of the instruments, and advances in synthesis and data interpretation freed the sounds from being tied to simple causal definitions.

Most projects in such electronic musical "wearables"[2,3] come under the rubric of "interactive

Figure 1 A simple one-man marching band setup (left); an example of pre-electronics wearable technology for musical expression (right)

— For position only —

dance."[4] An early example[5] is found in the work of composer Gordon Mumma, who adorned dancers with accelerometers to control analog synthesizers in performances of the 1960s. The well-known performance artist Laurie Anderson publicized these concepts in her shows of the 1980s,[6] using active apparel such as body suits adorned with percussive pickup transducers and neckties with embedded music keyboards. In the 1990s, several systems of this sort appeared. Many, such as Mark Coniglio's MIDIdancer,[7] The Danish Institute of Electronic Music[8] (DIEM) digital dance interface, and the Yamaha Miburi,**[3] were based around placing a set of resistive bend sensors across the dancer's joints to obtain dynamic articulation. Because the Miburi was a commercial product, it was packaged as a complete system, including finger controllers for each hand, a wireless interface, an embedded synthesizer, and a set of shoes with piezoelectric taps at the toe and the heel, with each shoe wired to the central belt-pack transmitter.

The foot of a trained dancer is a very expressive, multimodal appendage, capable of articulating much more than simple taps. Shoe interfaces for musical performances, however, were dominated by such tap implementations[9] and, until now, have not appreciably diversified from the toe-heel piezoelectrics.

Different applications have resulted in the adoption of other technologies for foot sensing, although essentially all of these instances concentrate on sensing only a small set of particular parameters. For example, podiatric treatment centers and product development groups at sports shoe companies use densely pixilated pressure sensors[10] to observe the dynamic pressure distribution on the shoe soles during walking and running. In these applications, the shoe is often tethered to a data acquisition system through a multiconductor cable. Much coarser pressure sensor arrays (e.g., sensing at only a few places) have been used in portable commercial products, such as devices to warn patients with podiatrial neuropathy about potentially damaging footfalls[11] and shoes to interactively coach a golfer on his or her dynamic balance.[12] A pressure-sensing overshoe has also been incorporated in “Cyberboot,”[13] developed at the National Center for Supercomputing Applications (NCSA) to incorporate foot gesture into virtual reality installations. The “Fantastic Phantom Slipper”[14] was an installation that used a pressure-sensing shoe with an active IR (infrared) optical system that tracked translational position across a small area, enabling users to step on animated insects that were projected onto the floor. Retrofits to jogging sneakers are now being brought to market that use inertial sensors for quantifying footfalls[15] and estimating elapsed distance (e.g., pedometry).[16]

The “expressive footwear” device developed in the MIT Media Lab Responsive Environments Group breaks these niches by using a diverse sensor suite to measure many (16) different parameters at the foot, detecting essentially everything that the foot is able to do, and telemetering the data back to a remote host computer in real time, leaving each shoe entirely untethered. Most human-computer interfaces concentrate on precisely measuring gesture expressed by the hands and fingers, devoting little, if any, attention to the feet. We have developed an interface that breaks this tradition, by measuring many parameters articulated at the foot.

The sensor system and shoe hardware

Our instrumented shoe was initially proposed[17] in 1997, then refined[18,19] in 1998, and perfected[20] in 1999. Figure 2 shows a diagram of the sensor system for our current shoe. Figure 3 shows a photograph of our original shoe system from 1997, grafted onto a Capezio Dansneaker**, and Figure 4 shows our final design affixed to a Nike *Air Terra Kimbia* (the electronics are normally obscured by a protective Lucite** cover, which was removed for this photograph). Figure 5 shows a close-up of the final version of the shoe electronics card, which can be seen to have advanced considerably beyond the initial working prototype of Figure 3.

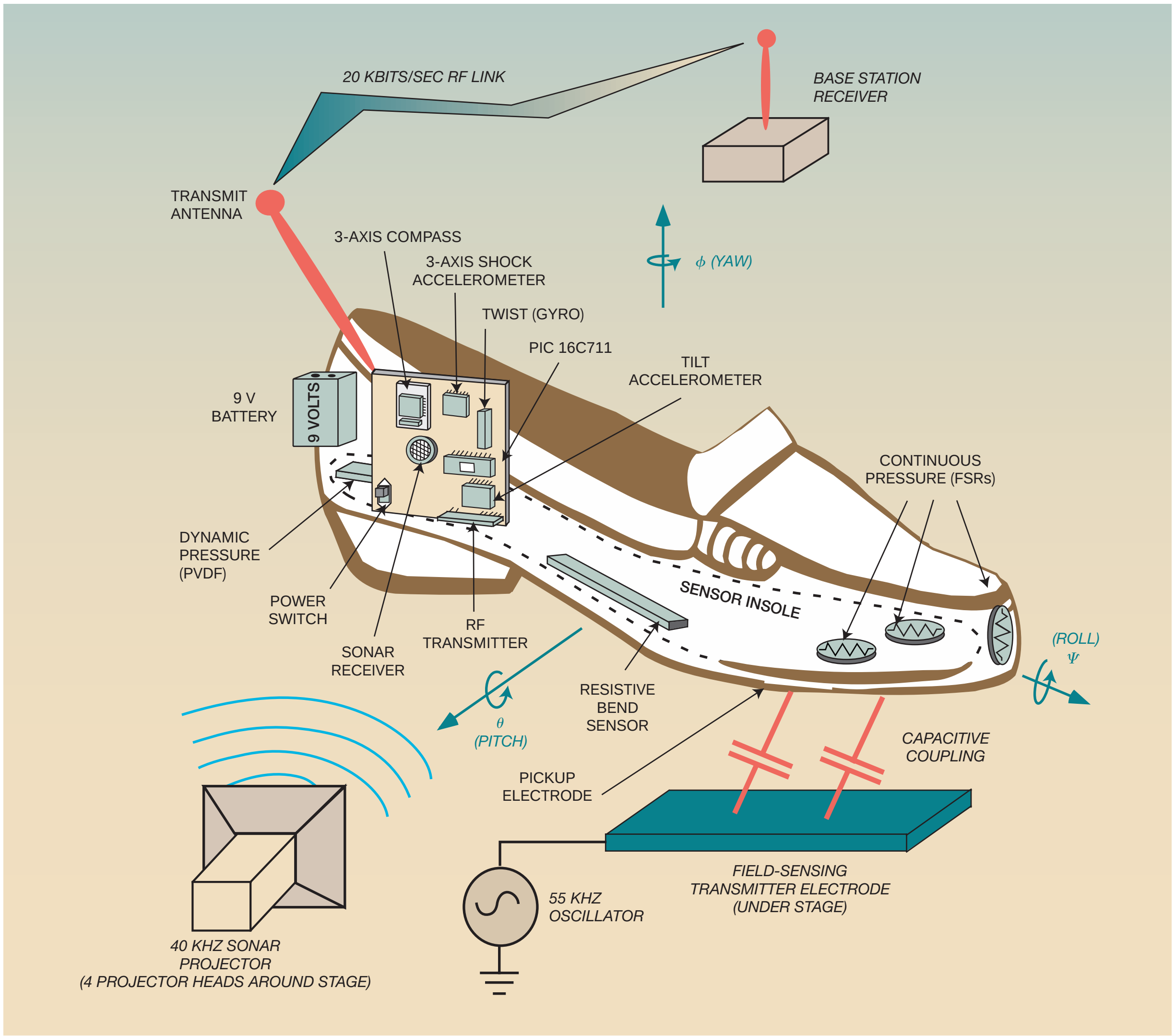
Shoe design and fabrication. A standard foam insole (represented by a dotted line in Figure 2) is embedded with an array of tactile sensors. Two standard force-sensitive resistors (FSRs)[21] are placed at the left and right in the forward region of the shoe, yielding continuous pressure there and responding to the dancer’s rocking of the foot side-to-side. Another FSR is placed forward of the toes, at right angles to the sole so it responds to downward pressure during pointing, when the shoe is vertical. Originally, this sensor was also inside the shoe compartment, but was moved outside for more reliable operation, since its performance varied considerably across different dancers’ feet. For easier integration, a more malleable “FlexiForce**”[22] FSR was used here (its foil cable is seen running across the side of the sole in Figure 4). At the heel, where dynamic pressure is more relevant, we placed a strip of PVDF (polyvinylidene fluoride),[23] a piezoelectric foil that responds to changes in force.[24] Two back-to-back resistive bend sensors,[25] which were placed across the middle of the insole behind the toes, measured the sole’s bidirectional bend.

A strip of copper mesh adhering to the bottom of the insole acted as a pickup electrode, capacitively coupling to transmitting electrodes, placed on the stage, that broadcast a constant sinusoidal signal at ≈55 kHz. When the dancer is above one of these plates, the signal received at the shoe decreases with the distance of the shoe from the plate,[26] giving an indication of the height of the shoe above the stage. Another electrode (not shown in Figure 2) is placed above the insole, just below the dancer’s foot, and is connected to the local electronics ground. This breaks the symmetry[27] between the pickup electrode, isolated below the insole, and the local shoe electronics ground, which is now effectively coupled to the dancer’s body. The dancer, in turn, is ambiently coupled to the house ground, enabling current to flow from the transmitter plates into the shoe, hence allowing the shoe system to capacitively receive the transmitted 55 kHz signal. The height of the foot is inferred from the detected signal strength.

A small (2¼" × 3¼") circuit board is affixed to the outside edge of the shoe on a metal mount, containing additional sensors and electronics. In our original design, the orientation of the foot at an angle,

Figure 2 Functional diagram of the Expressive Footwear electronics and sensor suite

— For position only —



ϕ, about the vertical when the foot was nearly level was obtained from an 1525 analog electromechanical compass,[28] a small gimbaled magnet with quadrature position measured by a pair of Hall sensors, manufactured by the Dinsmore Instrument Corporation in Flint Michigan. This monitored the orientation of the foot relative to the ambient (Earth's) magnetic field. While the Dinsmore device was adequate for capturing slower motion during initial operation, after several hours of use the mechanics would start to fail and the gimbal would stick. The large forces and shock impulses encountered at a dancer's foot are quite hostile to any fragile devices. In subsequent versions, the electromechanical compass was replaced with an all-solid-state device using permalloy bridge sensors, the Honeywell HMC2003 3-axis magnetic sensor,[29] which we modified[30] for 5-volt operation and higher gain. Although this sensor was quite reliable and gave wonderful, prompt 3-axis rotational response (another degree-of-freedom above the Dinsmore), permalloy bridges can drift over time as the sensing elements lose their magnetization. Therefore, a set of "strapping" pins was provided on the shoe card. By momentarily con-

Figure 3 The original working prototype shoe

— For position only —

Figure 4 The modern, perfected shoe with protective electronics cover removed

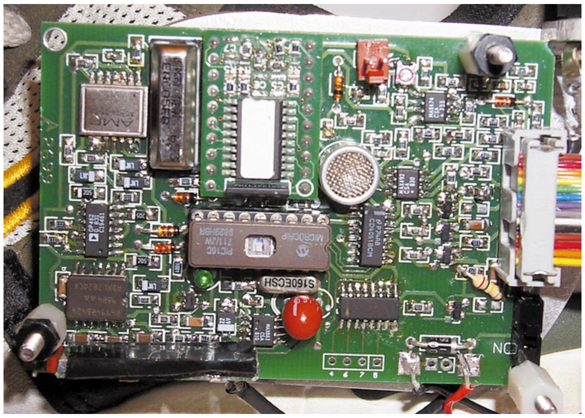
— For position only —

necting an 18-volt source across these pins, all magnetic bridges would be subject to a brief current pulse that would magnetically saturate the permalloy, strapping it to maximum sensitivity. Over normal usage, this strapping procedure would be adequate for at least several days, if not weeks, of operation.

Because spins are important gestures to detect, we mounted another rotational sensor, a compact gyroscope (a Murata GyroStar** vibrating-reed device[31]), on the sensor board, aligned with the axis of the ankle. This provided a direct measurement of angular rate about the vertical, giving clear response to spins and twists.

Figure 5 A close-up of the most recent sensor circuit card

— For position only —



A 2-axis, ±2 G (where G is the acceleration of gravity) MEMs (microelectromechanical systems) accelerometer from Analog Devices (the ADXL202)[32] measured the tilt of the shoe with respect to the gravity vector and responded to the moderate accelerations of foot swings. Impact shocks and kicks, at higher G levels, were measured in 3-axes by a triple piezoelectric accelerometer (the ACH-04-08-05 from Measurement Specialties).[33]

A small (1 centimeter diameter) piezoceramic sonar receiver (e.g., the Polaroid 40KR08[34]) detects 40 kHz pings sent from as many as four locations around the stage. By timing the reception of their first arrival, the translational position of the shoe can be tracked. The current shoe system is able to receive pings across a distance of roughly 20 feet using our current projectors, which are standard 1.5-cm diameter 40 kHz piezoceramic sources ganged in pairs. Additional range can be attained with more powerful emitters. With four independent projectors, at least one shoe is generally able to detect the signals from at least two projectors in our present performance configuration (see the section on dance applications later in this paper), fixing the dancer's position on the plane of the stage.

A "Peripheral Interface Controller" PIC 16C711 microcomputer from Microchip Systems, clocked at 16 MHz, is embedded onto the shoe card to digitize all signals and produce a serial data stream, which is broadcast to a base station through a small radio frequency (RF) transmitter, currently the "TX" series from Radiometrix.[35] Each shoe streams data at a separate frequency (418 and 433 MHz). The 20 Kb/s

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