

HYBRID TECHNOLOGY PLATFORMS AND INTEGRATED SYSTEMS

Article 3: Sensor Architectures for Interactive Environments

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Abstract As microelectronics have escalated in capability via Moore's Law, electronic sensors have similarly advanced. Rather than dedicate a small number of sensors to hardwired designs that expressly measure parameters of interest, we can begin to envision a near future with sensors as commodity where dense, multimodal sensing is the rule rather than the exception, and where features relevant to many applications are dynamically extracted from a rich data stream. This article surveys a series of projects at the MIT Media Lab's Responsive Environments Group that explore various embodiments of such agile sensing structures, including high-bandwidth, wireless multimodal sensor clusters, massively distributed, ultra-low-power "featherweight" sensor nodes, and extremely dense sensor networks as digital "skins". This paper also touches on other examples involving gesture sensing for large interactive surfaces and interactive media, plus overviews projects in parasitic power harvesting.

Index Terms— Sensor Networks, Energy Harvesting, Large Interactive Displays, Computer-Human Interaction, Ubiquitous Computing

1.1 Introduction

The digitally-augmented environments of tomorrow will exploit a diverse architecture of wired and wireless sensors through which user intent, context, and interactive gesture will be dynamically extracted. This article outlines a decade of

research conducted by the author and his team at the MIT Media Lab's Responsive Environments Group that explores such sensor infrastructures for creating new channels of interactivity and expression.

1.2 Interactive Surfaces

My earliest experiments with interactive environments evolved from heavily wired systems that I developed for interactive media installations, as shown in Figure 1. Starting in 1994 with an activated chair that exploited transmit-mode electric field sensing to produce musical response to body posture and dynamics [1], I evolved a suite of interactive stations for the 1996 debut of the *Brain Opera* at Lincoln Center [2] that encompassed installations such as an array of over 300 networked multimodal percussion sensors (the *Rhythm Tree*) and a handheld baton controller that incorporated tactile, inertial, and optical tracking sensors (in many ways, a forerunner of the currently popular Nintendo Wii).

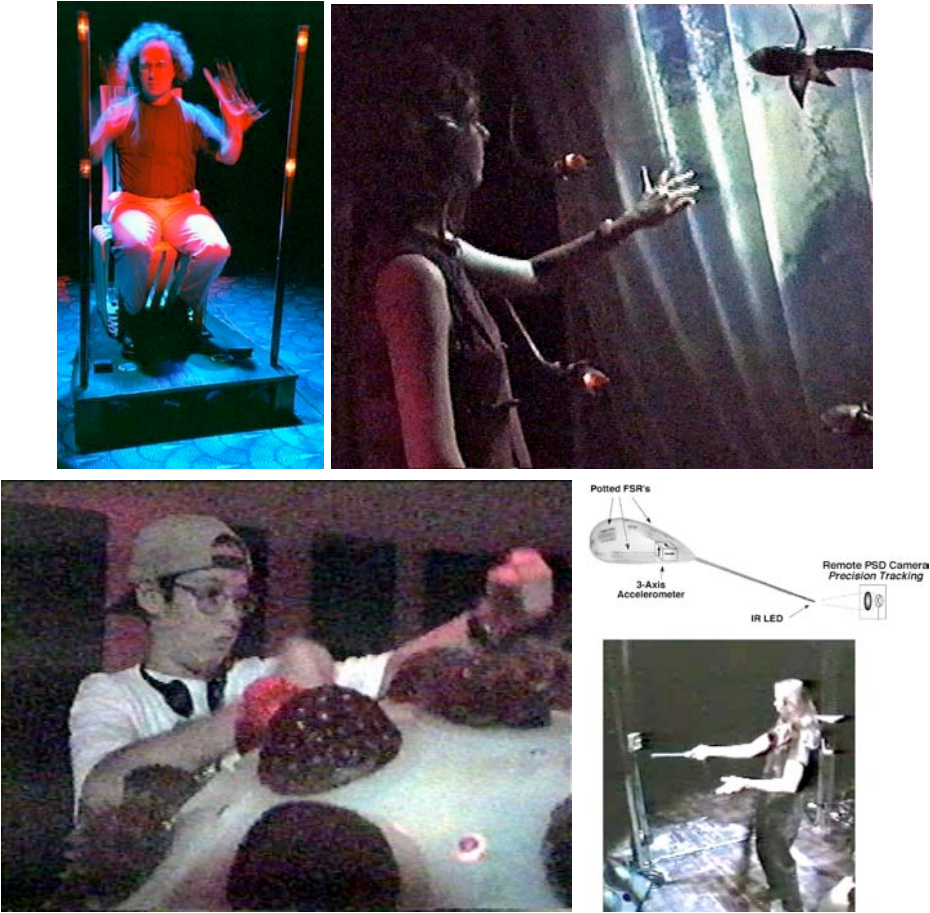


Figure 3-1. The Sensor Chair (top left), The Gesture Wall (top right), a small segment of the Rhythm Tree (bottom left), and the Digital Baton (bottom right – diagram and in performance)

One Brain Opera installation, the *Gesture Wall*, used an array of capacitive electrodes for sensing free-gesture atop interactive walls. This project sparked a deeper research interest into large interactive surfaces for public settings. As wall-sized displays decrease in cost, they will become more ubiquitous and eventually interactive. As opposed to the cloistered personal space provided by common video kiosks, large interactive displays naturally encourage collaborative activity. In public settings, small crowds typically congregate around such active walls, as individuals interacting with the displays effectively become performers, playing off their spontaneous audience.



Figure 3-2. The LaserWall at SIGGRAPH 2000 (bottom) and the Tap Tracker Window in the Innovation Corner at Motorola's iDEN Lab in Florida (top)

During the late 90's, my Responsive Environments research group developed a pair of systems (Figure 2) that retrofit large displays to track the position of bare hands [3]. The *LaserWall* used a low-cost scanning laser rangefinder mounted atop a

corner of the display to create a sensitive plane just above the display surface. As the rangefinder's detection was synchronously locked to the modulated laser, this system was insensitive to ambient light, and would measure the 2D position of the user's hand out to roughly 4 meters at a 30 Hz scan rate. A subsequent system used an array of 4 contact microphones fixed to a large sheet of glass to determine the position of impacts from unstructured knocks and taps [4]. Realizable as a digital audio application without requiring special hardware, a set of simple heuristics determined the nature of the impact (e.g., hard tap, knuckle knock, or fist bash) and estimated the position of the impact from the differential time-of-arrival of the structural-acoustic wavefront at the transducer locations, countering the effects of dispersion in the glass. Producing resolutions on the order of 3 cm across active areas spanning more than 4 square meters, this system enabled users to interact with a large display via simple, light knocks. As the plate and bulk waves launched by the knock propagate within the glass, this system only requires pickups on the inside of the glass, leaving the (potentially outdoor) outer surface free of any hardware and completely available for interaction.



Figure 3-3. The Magic Carpet Installation at the Boston Museum of Science (left) and taping of the piezoelectric wire to the bottom of the carpet (right) before installation at the MIT Museum

During development for the Brain Opera, I also became interested in interactive floorspaces. In 1997, this resulted in an environment for interactive music called the *Magic Carpet* [2,3] (Figure 3) that measured the position and dynamic pressure of a user's feet with a dense grid of piezoelectric cable laid underneath a 6-by-10 foot section of carpet. In order to make this environment immersive, upper body motion was measured by a pair of Doppler radars [2,5], which provided a rough estimate of the amount of motion, velocity, and mean direction of the objects within their beam. In contrast to conventional video approaches, although the information that the Dopplers provided was quite coarse, they were insensitive to illumination or clutter and required very little data processing to produce useful parameters.

1.3 Wireless sensor clusters

Starting in the late 90's, my research interests have increasingly encompassed

wireless systems and sensor networks. Wireless sensors are foot soldiers at the front lines of ubiquitous computing. Within this rubric, however, there is still a wide hierarchy of platforms suited to different applications and demarked by their physical footprint and energy requirements, from complex, multimodal sensor clusters sporting a high bandwidth radio down to simple sensors built into a passive RF tag. The MIT Media Lab's Responsive Environments Group has produced a wide range of such sensor systems that enable embedded computing to diffuse into various kinds of smart environments.

Sensors have followed a corollary of Moore's Law as they have dramatically decreased in size and cost across recent decades. Rather than dedicate a small number of sensors to hardwired designs that expressly measure parameters of interest, we can begin to envision a near future with sensors as commodity - where dense, multimodal sensing is the rule rather than the exception, and where features relevant to many applications are dynamically extracted from a rich data stream. Designers can now begin to embed a rich sensor package, of diversity previously seen in heavy platforms like robots or satellites, into the form factor of a wristwatch.

My first exploration of this principle was a shoe (Figure 4, top) for interactive dance [6]. As previous electronic footwear tended to concentrate on only one type of sensor (e.g., pressure sensors for tap dancing or inertial sensors for pedometry), my design was an expression of integration and diversity, in that I wanted to see how many different kinds of sensors I could practically embed into the constrained environment of a dancer's footwear with a real-time wireless data transfer coming directly from the shoe. The first working design, produced in 1997, was an early example of a multimodal, compact wireless sensor node of the sort now common in sensor networks. As this device incorporated a suite of 16 sensors that measured various inertial, rotational, positional, and tactile degrees of freedom, it was able to respond to essentially any kind of motion that the dancer would make. The sensor diversity proved to be extremely worthwhile when devising software behaviors that responded to the dancer's motion via music - we were able to fairly easily map any kind of podiatric motion the dancer made into a causal audio response with a straightforward rulebase.

To further explore applications of such dense wireless sensing, my group evolved an adaptable stacking architecture [7] a few years ago, and collaborated with the NMRC Laboratory (the National Microelectronics Research Institute, now called the Tyndall Institute) in Cork Ireland in developing a roadmap to shrink the electronics into a sub-cm volume [8]. Each layer of our Sensor Stack is dedicated to a particular flavor of sensing. For example, the inertial layer features a full 6-axis inertial measurement unit (IMU) on a planar circuit card and includes passive tilt switches for efficient wakeup, the tactile board supports a host of piezoelectric and piezoresistive pressure and bend sensors, and the environmental board features a variety of photoelectric and pyroelectric sensors, a compact microphone, and a small cell phone camera. Although our Stack has enabled many different sensing projects (including a collaboration with the Massachusetts General Hospital to build a gait analysis laboratory into a compact shoe-mounted retrofit [9], shown in Figure 4 middle), our current research with the Stack centers on sensor-driven power management.

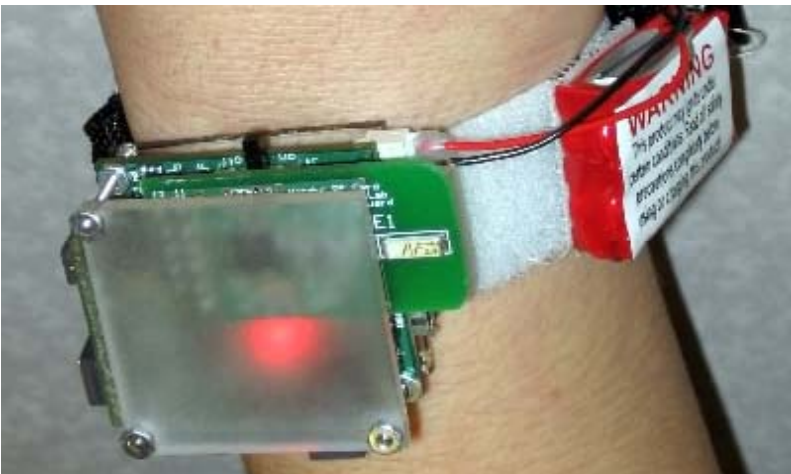


Figure 3-4. Wireless wearable sensor nodes. The 1998 version of the Expressive Footwear wireless sensor shoe for interactive dance (top), the 2004 GaitShoe (middle) for wearable biomotion analysis with the Sensor Stack mounted at the heels, and the recent compact wireless Senseable IMU (bottom) for interactive dance ensemble performance and sports monitoring.

While such multisensor platforms provide a rich description of phenomena via several different flavors of measurement, extending battery life mandates that the sensors can't be continually powered, but must rather spend most of their time sleeping or turned off. Accordingly, we have developed an automated framework that we term "groggy wakeup" [10] where, by exposing an analysis to labeled data from particular phenomena to be detected and general background, we evolve a power-efficient sequence of hierarchical states, each of which requires a minimal set of activated sensors and calculated features, that ease the system into full wakeup. Accordingly, the sensor system only comes full on only when an appropriate stimulus is encountered, and resources are appropriately conserved – sensor diversity is leveraged to detect target states with minimal power consumption.

We have recently deployed another wearable sensor node in versions tailored to interactive dance ensembles and high-speed motion capture for sports medicine [11]. Able to accommodate up to 25 nodes that update full state to a remote base station at 100 Hz, these compact nodes (the size of a large wristwatch – Figure 4 bottom) feature a full 6 axes of inertial sensing. The dance version also provides a capacitive sensor that can determine the range between pairs of nodes (out to a half-meter or so). The more recent sports version also features both high and low G accelerometers and high-rate gyros along with a tilt-compensated compass for directly determining multipoint joint angles and in-processor flash memory that enables synchronized onboard recording of all sensor readings at 1 KHz for 12 seconds (sufficient to monitor a basic athletic motion – e.g., pitch, swing, or jump) with subsequent wireless offload of data from all nodes. We have also recently made a simpler version of this system for interactive exercise, featuring a set of wireless ZigBee accelerometers worn at the limbs that communicate with a mobile phone running a compiled interactive music environment [12].

Although sensors indeed grow progressively smaller and cheaper, a platform as diverse as a fully outfitted Stack is still somewhat expensive, potentially running into hundreds of dollars. Another avenue through which sensors diffuse into the world is via an orthogonal axis – where ultra low-cost wireless sensors measure very few parameters, but are so cheap that they can be very widely deployed. One such "featherweight" sensor system that we have developed, shown in Figure 5 (left), is a compact acceleration detector that sends a narrow RF pulse when it is jerked [13]. Although there are many applications for such a device (e.g., activity detection in smart homes [14]), we have used it to explore interactive entertainment in very large groups, where these cheap sensors can be given out with tickets, and real-time statistics run on incoming data can discern ensemble trends that facilitate crowd interaction. As the electronics are directly woken up by the sensor signal, the batteries in these devices last close to their shelf life.

By exploiting a passive filter conditioned by a nanopower comparator, we have developed more generalized systems that are directly activated by low-level sensor signals in particular spectral bands. Termed "quasi-passive wakeup", this initiative has developed a micropower, optically-interrogated ID tag (Figure 5, right) for applications where standard RFID doesn't perform (e.g., in the presence of metal or with very limited surface area) [15,16]. Our "CargoNet" (Figure 5, bottom) device [17] is a recent implementation of this principle. Designed for low-cost, long-duration monitoring of goods transiting through supply chains, this node monitors

temperature and humidity once per minute, continually integrates low-level vibrations, and wakes up asynchronously on shock, light level, sound, tilt, or RF interrogation above a dynamically adaptable threshold. Accordingly, the tag stays in a very low-power sleep unless it wakes up to do periodic monitoring or encounters significant phenomena (e.g., a drop or hit, something breaking, container breach, or RF interrogation request). The CargoNet can automatically “numb” its sensitivity to prevent redundant wakeup in environments with significant steady-state background (e.g., continual vibration, light, or noise). Tests of this platform in various shipping conveyances have exhibited average power requirements of under $25 \mu\text{W}$, suggesting a circa 5-year lifespan from a standard lithium coin cell battery.



Figure 3-5. An ultra low-cost wireless motion sensor for crowd interaction (top left), quasi-passive optical wakeup tag (top right), and a CargoNet Active RFID Sensor Tag (bottom).

1.4 Energy Harvesting

Other sensors dispense with the battery entirely, and are powered through inductive, electrostatic, or radio interrogation like RFID tags. We have explored a variety of small, chipless sensor tags that map their response onto their resonance frequency for applications in human-computer interfaces [18], an example of which is shown at left in Figure 6. A recent project, currently under development, is seeking to develop a very low cost, passive RFID tag based on Surface-Acoustic-Wave (SAW) devices for precise (e.g., 10's of cm) radio localization for objects in buildings and rooms. These tags are addressed by a series of base stations that emit a coded sequence of RF pulses that correlate with programmable reflectors fabricated onto the SAW waveguide. A correlation between the transmit sequence and the tag's response at the base stations determines range, and multiple base stations triangulate to determine tag position. Initial fabrication of these "μTags" has been performed [19], and they are now undergoing characterization and test (Figure 6, right).

Going further, systems that are able to scavenge energy from their environment hold the promise of perpetual operation, with their longevity limited by component lifetimes rather than the capacity of an onboard energy store. Our forays into power scavenging (Figure 7) began in 1998 with piezoelectric insoles that produce power as the wearer walks, followed a couple of years later by a radio powered by a button push for batteryless remote controls [20].

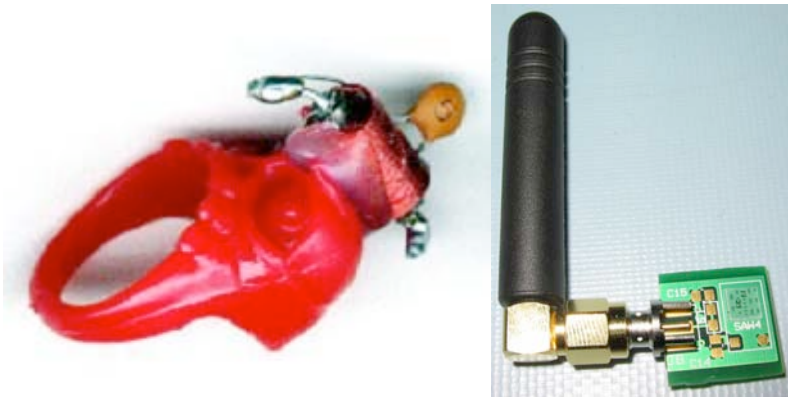


Figure 3-6. A passive LC tag mounted on a ring for finger tracking and HCI applications (left) and a prototype passive localization μTag mounted on an evaluation board (right)

Our recent research in this area has established a new field called parasitic mobility [21], which interprets energy harvesting for mobile sensor networks as an adaptation of "phoresis" in nature, where nodes can actively attach to a proximate moving host (like a tick), passively adhere to a host that comes into contact (like a bur), or provide a symbiotic attraction to a passing host that makes them want to carry the sensor package (e.g., by attaching it to something useful like a pen). Although parasitic nodes can be very lightweight, since the nodes only need sufficient energy and agility to attach to a nearby host and determine where it is

bringing them, our existing active prototypes (sized on the order of a 3 cm cube) are of a scale more appropriate for vehicles rather than animate carriers – a situation that will change as the nodes grow smaller.

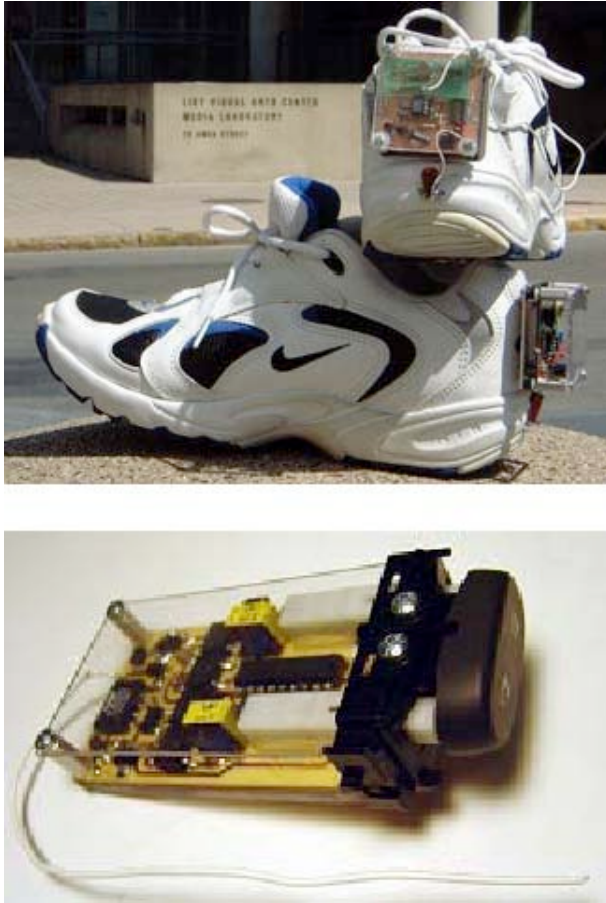


Figure 3-7. Power generating shoes with piezoelectric insoles from 1998 (top) and a self-powered dual RF push button for a wireless car window controller (bottom)

1.5 The PLUG

Another way to power to a sensor network in home, workplace, or factory environments is to tap into the existing power grid. As the cost of sensors decreases, it may not be unusual to see them incorporated into devices that are mainly intended for other purposes in order to widen their domain of application. Accordingly, we have recently embedded a multimodal sensor network node into a common power strip (Figure 8 - top) [22].

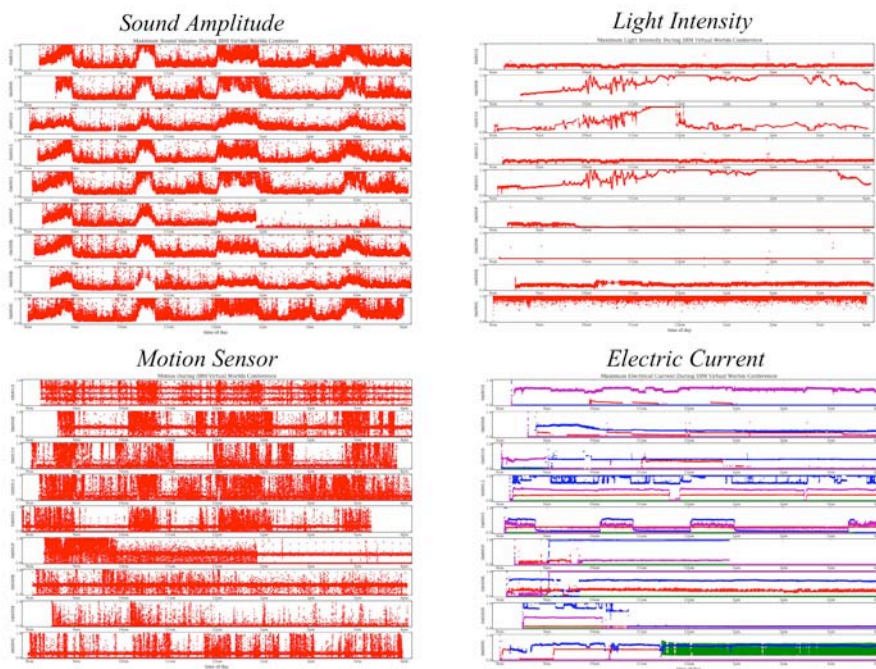
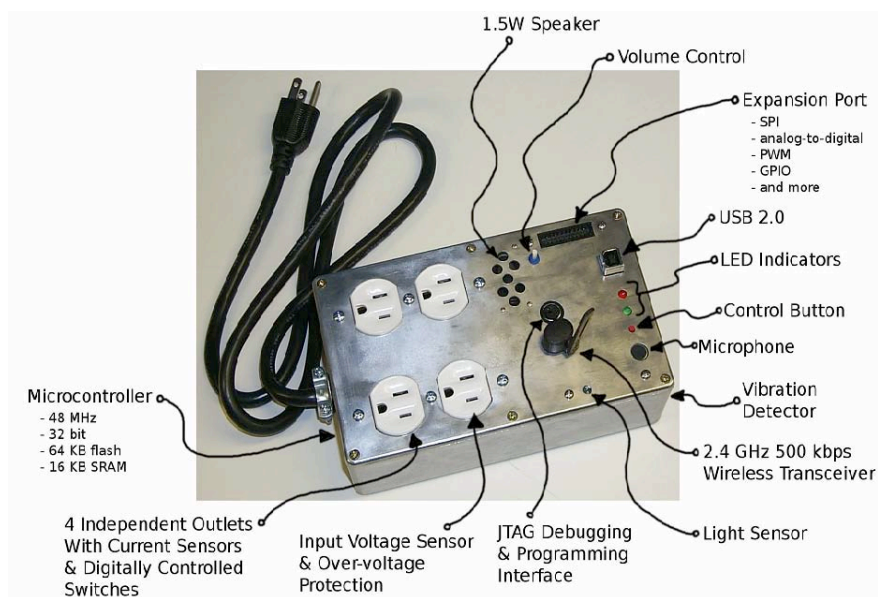


Figure 3-8. The prototype PLUG (top) – piggybacking a multimodal sensor network node onto a power strip and multimodal data from 9 PLUG nodes stationed at demos during an 8-hour public event

This device has access to power (and potentially networking) through its line cord, can control and measure the detailed current profile consumed by devices plugged into its outlets, supports an ensemble of sensors (microphone, light, temperature, and vibration sensors are intrinsic, and other sensors such as thermal motion detectors and cameras can be added easily), and hosts an RF network that can

connect to other PLUG sensors and other nearby wireless sensors (accordingly acting as a sensor network base station). Figure 3-8 (bottom) shows PLUG data plotted from 8 AM to 4 PM (spanning the duration of a 200-person public event held in our auditorium). Data from nine PLUGs are shown, each of which was installed at a demo station in the atrium outside of the theater where the talks were held. The structure of the event can be noted directly from the data, where sound amplitude and motion are seen to increase markedly when the talks aren't in session and the audience is milling about in the atrium. PLUGs located near the windows exhibited a clear common daylight curve, while those located under artificial lighting exhibited more constant illumination, barring any modulation or deactivation of the light source. The electric current profile is very varied, showing clear differences between devices that pull constant current, devices being turned on and off, and devices (like computers, monitors, or projectors) that exhibit dynamic current draw.

We have leveraged the PLUG platform to explore a variety of ubiquitous computing applications, such as a distributed conversation masking system [23] and new approaches to browsing sensor network data by tying it metaphorically to events in virtual worlds (an aspect of what we term “Dual Reality” [24]).

1.6 Sensate Media

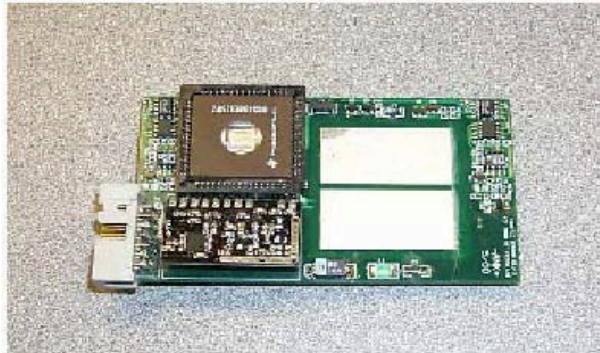
In addition to shrinking the sensor node size and power requirements, another axis of diminishing scale can be the distance between nodes on a sensor network. Rather than building sensor nets with nodes many meters apart (a standard deployment for sensor networks), we are also exploring an interpretation of sensor nets as electronic skins, where the nodes are cm or mm apart. Taking inspiration from biological skin, the copious data generated from a field of multimodal receptors in such sensate media [25] is reduced locally in the network across the physical footprint of the stimulus, and then routed out to computational elements that can take higher-level action. Promising revolutionary applications in areas like prosthetics, robotics, and telepresence, this extreme vision of scalable pervasive computation embedded onto surfaces encourages dramatic advances in microfabrication, embedded computing, and low power electronics. We have fielded several platforms to explore this concept (Figure 9), including a dense planar array of configurable “pushpin” computers that we have used to study localization from commonly-detected background phenomena [26], a sphere tiled by a multimodal sensor/actuator network used to study co-located distributed sensing and output [27], a sheet of interconnected small, flat multimodal sensor nodes fabricated on flex substrate [28], and a floor tiled with pressure-measuring sensor network nodes [29] that detect and characterize footsteps, then route high-level parameterizations off the floor tile-tile, avoiding complex cabling and multiplexing schemes.



Figure 3-9. Several Dense Sensor Networks - the PushPin Computer (top left), the Tribble (top right), a sensor network “skin” with elements fabricated on flex substrate (bottom left), and a few of the Z-Tiles interactive floor (bottom right) pursued in collaboration with the University of Limerick

In 2000, we also explored building a wireless sensor network ‘skin’ into a sensate roadbed that’s able to infer dynamic road conditions and the statistics of passing traffic [30,31]. Sporting a permalloy magnetic sensor that can detect the disturbance in the Earth’s magnetic field caused by the passing of the automobile’s ferrous chassis and engine block overhead, this device is able to count cars and estimate rough speeds (assuming an average vehicle size). The addition of temperature and capacitive dielectric sensors can also hint at the presence of ice on the roadbed. As the measurements don’t need to be updated instantaneously, a carrier-sense-multiple-access (CSMA) network can be used that allows the nodes to dump their accumulated data at different intervals, eliminating the need for network synchronization and a receiver on the nodes.

Our prototype tests (Figure 9) have indicated that, with proper duty-cycling of the magnetic field sensor and circa 15-minute data uploads to a nearby base station (assumed to be located at the roadside within 500 meters or so), the average node’s current draw will be on the order of 15 μ A, enabling them to last up to a decade with an embedded hockey-puck-size lithium battery, a lifespan well-suited to the periodic need for road resurfacing. As the node cost will be on the order of 10’s of US\$ for large quantities, it becomes feasible to instrument a city center with these devices for a few million dollars, a modest cost in comparison with the expense of the physical road itself.



Morning Rush Hour, 60 Vassar Street, Eastbound, May 22, 2000

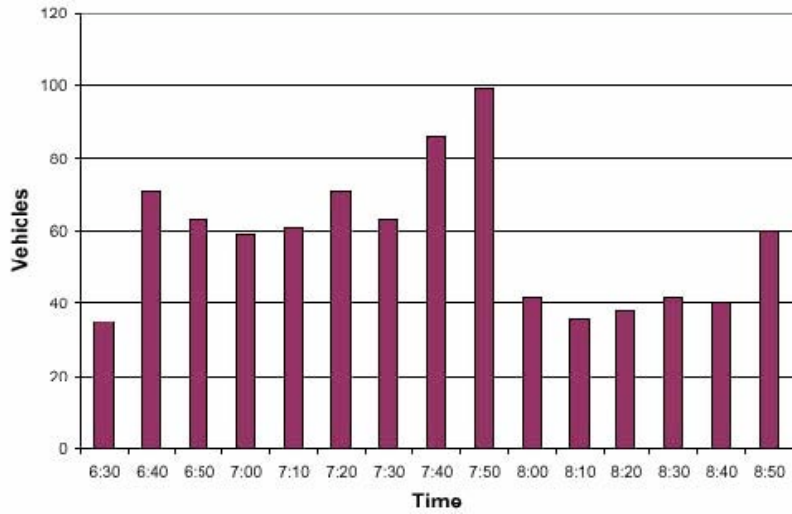


Figure 3-10. The Sensate Roadbed prototype sensor node (top) encased in a Delrin enclosure for tests in a pothole on Vassar St. (center), and the passing car count from this node during the morning rush hour (bottom), showing the development of a traffic jam around 8 AM.

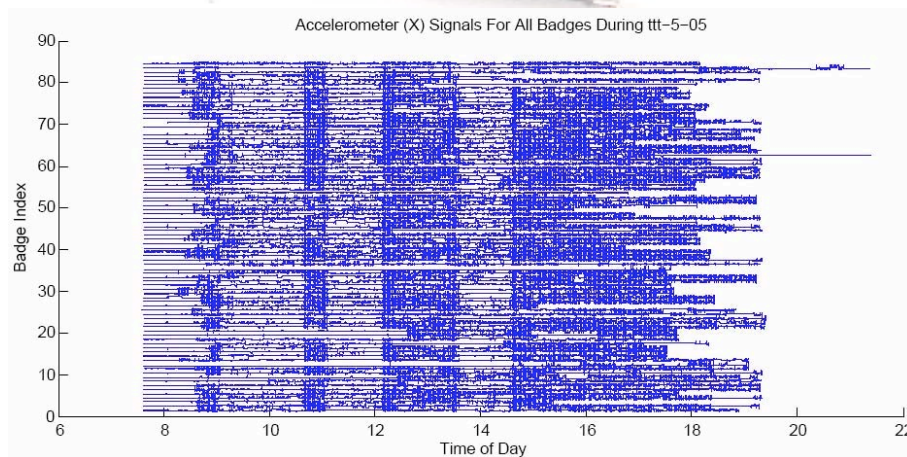


Figure 3-11. An UbER-Badge (top) and accelerometer data logged from all badges worn at a recent Media Lab function - the structure of the event (talk sessions, breaks, open house) is clearly evident.

1.7 Badge Platforms

A recent wearable device that we developed, called the UbER-Badge, was designed as a flexible platform that can be used to facilitate interaction at large social events as well as a tool to analyze human dynamics [32]. Sporting a multitude of features, the badge includes a large, highly-visible LED display for scrolling text and showing simple animations, a line-of-sight IR port for communicating with nearby badges or active IR tags, and an onboard radio for wireless networking. These badges have been used by over 100 simultaneous attendees at several large Media Lab events. Although the badges facilitated applications such as wireless messaging, voting, and bookmarking of other badges or tagged demos during our open house, it was extremely effective at timekeeping during tightly-scheduled presentations, where

all badges in the audience flashed bright time cues to the speaker, becoming increasingly insistent as talks run over. The badges also continuously logged accelerometer and audio spectral data (see Figure 11). An analysis of our data [32] has indicated that the badges' measurements of body motion and voice characteristics, together with the IR person-person data, predict relevant aspects pertaining to user behavior (such as interest level) and can determine social context (such as affiliation with other users).

We are now finalizing a new system called "Spinner" [33] with hardware components that include a small badge (hosting IR, compass, microphone, and accelerometers), a wrist sensor (hosting accelerometer, compass, and Galvanic Skin Response [GSR] monitor) and a stationary network of multimodal sensors (including video and audio). Spinner seeks to enable automatic assembly of captured video that best fits a story-board "query" describing participants' activities projected onto an abstracted narrative "plot," with the affective/social context derived from the wearable sensors acting as primary keys to this query. In this fashion, a pervasive sensor network is used to derive a projection of the participants' daily life that best fits a story – indeed, through such emerging frameworks, we *all* become actors.

1.8 Conclusion

This article has presented several projects from the Media Lab's Responsive Environments Group that illustrate several approaches to sensor architectures for pervasive computing. The article has adopted the style of a high-level survey, omitting detail in favor of a broad presentation. Readers are encouraged to peruse the cited references for more information, including extensive overviews of related and prior work for each of the projects presented here. More details and video clips showing several of these systems in action can be downloaded from:

<http://www.media.mit.edu/resenv/projects.html>.

ACKNOWLEDGMENT

The author acknowledges the hard work of several generations of his students in the Responsive Environments Group, upon which much of this work is based. Most of these projects were supported by the Things That Think Consortium and the Media Laboratory's industrial partners.

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