On-Body Wireless Sensing for Human-Computer Interfaces

Prof. Joe Paradiso
Responsive Environments Group, MIT Media Lab

http://www.media.mit.edu/resenv
At a fascinating intersection

Ubiquitous Computing

Sensor Networks

Implantables

Wearable Computing
Topics

- Wearable Sensors
  - Sports Medicine & Entertainment

- Low Power Techniques
  - Quasi-Passive & Groggy Wakeup
    - Applications in Health and Supply Chain Monitoring
  - Passive RFID Tags for Precise Localization

- X Reality
  - Sensor networks connect real and virtual spaces
  - Virtual worlds for browsing reality

- Sensor-Enhanced Media Creation Sensor Networks for Social Computing
Sensing as Commodity

- Sensors are now becoming a commodity, and soon can easily be designed into most any device.
  - Rather than omitting them from a cost/complexity viewpoint, it begins to make more sense to just include them if there’s any suspicion that they could be needed.
  - This causes a shift in how sensors are used – rather than rely on only 1 or 2 sensors made a priori to measure particular quantities, many sensors will be used that don’t necessarily exactly measure the quantity of interest (especially as applications will become more general and evolve over time).
1997 - Expressive Footwear

17 Data Channels
Tilt, shock, rotation, height, bend, location, multipoint pressure
Measures 18 Parameters per foot
“Shuffle Index” vs. “Stride Excitement” via CART

Minimum Foot Inclination (deg)

Variation in Insole Force [normalized by bodyweight]
Real-Time Auditory Feedback

- Parametric Personal Music System
  - Always play ambient music
- Provide meaningful (and correcting) musical feedback when problematic gait changes arise.
Scaling to several dancers…

Capacitive proximity to 50 cm
6-axis IMU - 1 Mbps TDMA radio
100 Hz Full State Updates from 25 nodes

High Speed Sensor Fusion
Vocabulary of features
Capacitive Sensing System

- Capacitive system measures relative spacing between nodes
- Employs a “transmit mode” configuration
- One node transmits a sinusoidal pulse at 90kHz, others measure amplitude of received pulse
- Nodes trade roles as transmitters and receivers as arbitrated by the wireless basestation
- Sensitive up to 0.5 meter with bracelet-sized electrode and shared ground through the body
New Developments

- Full deployment at a rehearsal with 20 sensor nodes running on five dancers

- Feature extraction and mapping algorithms which are fed logged data at the sample rate to simulate real time operation
Rough Demo Mapping

- Audio rendered in real-time as features are calculated
- Runs on a 1.6 GHz G5 w. 1GB RAM

**Direct Features**

- Cross Covariance Between Each Pair of Dancers
- Mean Activity Level Of Individual Sensors
  - Average Over Peak Values
  - Average Over Lag Times
  - Average Over Entire Ensemble
  - Average For Each Dancer
  - Average For Each Limb Across Ensemble

**Intuitive Features**

- Similarity
- Global Activity Level
- Distance Metric Between Each Individual and Group

- Synchronicity
- Individual Activity Levels

**Musical Parameters**

- Violin
  - Trigger
  - Pitch
  - Loudness
  - Pan
- Bass Synth
  - Trigger
  - Pitch
  - Loudness
  - Flute Or Plucked String Run
Red Sox Spring Training

Biomotion measurement of a Red Sox Pitcher

*Modified sensors for high range and high sample rates*

- 3-axis 10,000 °/sec gyro
- 3-axis 120 G accelerometer
- 3-axis 10 G accelerometer
- 3-axis magnetometer
- 1 kHz synchronized sampling per node
  - 12 seconds recorded on flash at each node
• Acceleration at the wrist peaks well above 100g
• Most of this acceleration occurs in a 30ms window
• Equates to 30 samples for the modified inertial system, but only 5 frames on a 180Hz video capture system

Acceleration of the Pitch Above Captured at Three Critical Locations - Hand, Wrist, & Biceps

>100 g’s!!
Players Cluster

80-81mph Fastball

- Pitcher 1 Hand
- Pitcher 1 Wrist
- Pitcher 1 Upper Arm
- Pitcher 2 Hand
- Pitcher 2 Wrist
- Pitcher 2 Upper Arm

Peak Rotation Amplitude

Peak G Amplitude
Miniaturizing & Distribution

- Future of athletic broadcasts
  - Get content directly from point of expression
    - Sensor packs in figure skates, boxing glove, snowboard…
  - Map dynamic content (music, graphics, specs…)
- Future of exercise
  - Monitor lower, upper limbs, heart rate, etc.
  - Map interactive content
    - Synchs up and nudges participant to stay on track
- Therapy with interactive feedback
Interactive Music on N800

- Zigbee interface for N800
  - Easy implementation of wearable sensors (inertial, etc.)
- Pd (PureData) compiler for N800
  - Allows artists to graphically compose music interaction & synthesis
  - Produces C code (not interpreted)
  - Fast, efficient execution

Robert Jacobs’ M.Eng. Thesis - demos coming
Groggy Wakeup for Efficient Smart Sensor Systems

Automated Power-Efficient Sensor Hierarchy

Keep higher-power sensors OFF unless needed for detection decision

General on-node implementation

Power-efficient detection of gait phase
Groggy Wakeup for Efficient Smart Sensor Systems

Automated Power-Efficient Sensor Hierarchy

Trade Power Consumption with Detection Efficiency


Power-efficient detection of walking up stairs
Groggy Wakeup for Efficient Smart Sensor Systems  Ari Y. Benbasat

Automated Power-Efficient Sensor Hierarchy
Trade Power Consumption with Detection Efficiency

Figure 3. Power/accuracy tradeoff for decision trees and SVM
Tree Execution Running on the Stack in Real Time

2-level gait classifier tree during actual walking
The Disposable Wireless Sensors

- Very simple “featherweight” motion sensor
  - Cantilevered PVDF piezo strip with proof mass
  - Activates CMOS dual monostable when jerked
  - Sends brief (50 µs) pulse of 300 MHz RF
  - 100 ms dead timer prevents multipulsing
  - Can zone to within ~10 meters via amplitude
  - Ultra low power – battery lasts up to shelf life
  - Extremely cheap – e.g., under $1.00 in large quantity

Malinowski, Moskwa, Feldmeier, Laibowitz, and Paradiso - Presented at ACM Sensys 2007

- Dynamically adaptable thresholds
  - Adapts to environments with persistent stimuli
- Small and inexpensive
- Microampere current draw
  - 5 years on a single coin cell battery

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Measurement or Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shock Sensor</td>
<td>Potential impact damage</td>
</tr>
<tr>
<td>Vibration Dosimeter</td>
<td>Average low-level vibrations</td>
</tr>
<tr>
<td>Tilt Switch</td>
<td>Package orientation and shaking</td>
</tr>
<tr>
<td>Piezo Microphone</td>
<td>Events causing loud nearby sounds</td>
</tr>
<tr>
<td>Light Sensor</td>
<td>Container breach or box opening</td>
</tr>
<tr>
<td>Magnetic Switch</td>
<td>Package removed or box opened</td>
</tr>
<tr>
<td>Temperature Sensor</td>
<td>Overheating or potential spoilage</td>
</tr>
<tr>
<td>Humidity Sensor</td>
<td>Potential moisture damage</td>
</tr>
<tr>
<td>RF Wakeup</td>
<td>Query from reader or another tag</td>
</tr>
</tbody>
</table>

Table 1. List of sensors present on the CargoNet tag.
Power Harvesting Shoes

PVDF Stave
Molded into sole
Energy from bend
\[ P_{\text{peak}} \approx 10 \text{ mW} \]
\[ \langle P \rangle \approx 1 \text{ mW} \]

Flex PZT Unimorph
Under insole
Pressed by heel
\[ P_{\text{peak}} \approx 50 \text{ mW} \]
\[ \langle P \rangle \approx 10 \text{ mW} \]

Raw Power
circa 1% efficient
unnoticable

Responsive Environments Group
MIT Media Lab
1998 IEEE Wearable Computing Conference
Mobility in Sensor Networks

- Forefront research where sensor nets meet robotics and control
- Sensor clusters move to places to optimally:
  - Measure dynamic phenomena
  - Position relays to repair or patch broken network
  - Dump information at access points (portals)
  - Get recovered or recharged

What does power harvesting mean in a mobile system?

*Energy cost of moving atoms is much higher than moving bits...*
AES Roadmap

**Roadmap to Miniaturised Autonomous Sensor Networks**

- **2004**
  - Distributed Micromodule Platform
    - 3D PCB Stack
    - SMT assembly of Commercial Components

- **2005**
  - Autonomous Micromodule Platform
    - 3D MCM Stack
    - Bare Die Assembly of Commercial Components
    - Flip Chip Assembly

- **2006**
  - Micromodule Integration Platform
    - 3D Bare Die Stack of Commercial Components
    - Can be Planar
    - Thin Silicon
    - Thin Flexible Substrates

- **2007**
  - -3D WLP
    - Through Die Interconnect
    - Novel Substrates
    - Self Assembly

- **2008**
  - Intelligent Seed

Tyndall National Institute
Parasitic Mobility in Sensor Networks

Implications
- **Sensor clusters hitch rides** to places where they need to be to optimally:
  - Measure relevant phenomena
  - Relay information peer-to-peer
  - Dump information into portals
  - Get recovered or recharged

- Rapid diffusion of sensors across an environment
- System self-organizes to auto-dispatch nodes to desired regions

Innovations and Architecture
- Interpretation of Energy Harvesting in mobile networks
- Two flavors:
  - The Tick (e.g., jumps onto a car, attaches magnetically, then disengages)
  - The Bur (e.g., sticks to passing object, then shakes off)
- Contains GPS, RF, basic sensor suite

**Phoresis**

Paradiso & Laibowitz
Parasitic Mobility Research (ParaMoR)

- Paramor Hardware – small nodes with sensor suite (light, microphone, inertial, proximity, temperature, heat), GPS, RF communication, rechargeable power source, and minimal actuation for attachment/detachment
- Active nodes (ticks)
- Passive nodes (burs)
- Value-added nodes (pens)
- ParaSim – Software simulator to study behavior and evaluate control algorithms for parasitically mobile sensor nodes

Mat Laibowtiz
Precise, ultra low cost wide-area tracking of small passive tags for indoor localization
Will revolutionize asset tracking and supply chain operation, search & rescue, etc.

- Utilizing passive RFID surface acoustic wave (SAW) and low-cost radar technology.
- Target short-range (3-100m) applications
  - Expect single-measurement resolution of under 10 cm
- Multipath from reader dies out before tag responds
- 900 MHZ devices coming out of MIT MTL and nano labs
  - Now being characterized and tested

Jason LaPenta
Google for Reality

[Google search results for "my wallet"]

Find My Wallet
I got super drunk unless someone www.40thhings.co

Download My
My Wallet 1.4 M
a single, secure I www.softwareci.ca
Cached - Similar

Take My Wall
How do you track pocket. Then I li www.kiplinger.com

My Wallet free
My Wallet free d web passwords. I www.freedownload 25k - Cached - S

Pay By Touch
Pay Select your Kingdom - Engls https://webohroll

Hey! Where’s
TOPIC: college | Won’t Be Put On deadspin.com/... 307475.php - 93k
Public Misinformation...

“Human” Energy harvesting will do little for sustainability. It will only be valuable in extending/eliminating batteries in portable devices, wearable sensors, etc.
Sensor networks for energy conservation

- Leveraging dense sensor networks for optimal urban energy management
  - 40% of US energy is spent in buildings
  - Pervasive sensor/actuator network can work to minimize this
    - Optimize heating, AC, lighting for Person not room
    - Anticipating behavior & build usage models over time
  - My RA, Mark Feldmeier is now a MIT Martin Energy Fellow
    - Exploring ways to sense “comfort” to optimize distributed utility control
"After three thousand years of explosion, by means of fragmentary and mechanical technologies, the Western world is imploding. During the mechanical ages we had extended our bodies in space. Today, after more than a century of electric technology, we have extended our central nervous system itself in a global embrace, abolishing both space and time as far as our planet is concerned. Rapidly, we approach the final phase of the extensions of man - the technological simulation of consciousness, when the creative process of knowing will be collectively and corporately extended to the whole of human society, much as we have already extended our senses and our nerves by the various media."

*Marshall McLuhan - Understanding Media (1964)*

Electronic media (a.k.a. television) as an extension of the central nervous system
Sensor Networks as Extension of the Nervous System

Cast our awareness across space, time, scale, modality…
Sensor networks are the foot soldiers at the front lines of ubiquitous computing

At this point, few if any customers will buy an ensemble of “UbiComp” sensors

They will aggregate from established devices

– Home security, appliances, utility devices, entertainment…

*Just as the web sprouted from a networked ensemble of personal computers, true “ubicomp” will arise from an armada of networked devices installed for other purposes.*
Power Strips are Everywhere

- Needed in Homes, offices, especially the Media Lab!
- Sensors are becoming commodity items
  - Cost of adding sensors to a design is becoming incremental
- Power strips are ideal base platforms for hosting a sensor network
  - Ready access to power
  - Power line can be a network port
  - Can monitor the status of devices that are plugged in
PlugPoint – Power Strips as the backbone of a UbiComp Sensor Infrastructure

J. Lifton, M. Feldmeier, Y. Ono (Ricoh)

Collaboration with Ricoh Research

Power Line provides energy & comm
Monitor current profiles, Switch individual sockets Hosts basic sensors (mic, light, motion) Expansion Port for others Hub for wireless sensor network

Microcontroller
- 48 MHz
- 32 bit
- 64 KB flash
- 16 KB SRAM

4 Independent Outlets With Current Sensors & Digitally Controlled Switches

Input Voltage Sensor & Over-voltage Protection

JTAG Debugging & Programming Interface

1.5W Speaker

Volume Control

Expansion Port
- SPI
- analog-to-digital
- PWM
- GPIO
- and more

USB 2.0

LED Indicators

Control Button

Microphone

Vibration Detector

2.4 GHz 500 kbps Wireless Transceiver

Light Sensor
Army of Plugs

35 ON MEDIA LAB THIRD FLOOR
Darker implies more sound & movement
Rhythm of Lab

Incident Light

Sound Volume

Outlet Current
Sensor Networks for Linking Virtual and Real Worlds

X-Reality
Reality Taxonomy

Reality  Augmented Reality  Mixed Reality  Virtual Reality

real  virtual

All single realities.
Two complete realities that influence and leak into each other by means of ubiquitous sensor/actuator networks.
Reality Mappings

Allow for distortion, exaggeration, and metaphor.

Real World can be “browsed” in virtual space
Second Life as a the Virtual End of Dual Reality
Shadow Lab - Binding real sensor data to virtual worlds

Third floor of ML built in Second Life

ResEnv Lab rendered in detail - other areas currently derived from map

Sensor data piped in and interpreted as real-time graphic phenomena

Simple sensor apparitions to explore basic ideas
  - Energy use → height of fire
  - Activity (sound, motion) → whirlwinds
  - Active regions → higher walls
  - “Ghost” face → individual presence

Lifton 07

Josh Lifton - Building a virtual Media Lab in Second Life
Mobile User Interfaces for Sensor Networks

Browsing, querying, navigating through sensor net data

What are the interface affordances, displays, interaction modalities?

Privacy & Security?

Mobile platform inside of network vs fixed platform outside?

*McLuhan Extension of human senses*
Sensate Pervasive Imaging Network for Narrative Extraction from Reality

Unites wearable human sensing with video capture
Maps sensor data to high-level concepts for creation of meaningful video
  Investigates how humans perform this mapping (i.e., how they create stories and narrative)
Use of wearable sensing allows access to subject/data channels far beyond what can be achieved with standard image pixel processing

Mat Laibowitz - PhD in Progress
Overall System Diagram

User Interface

Story Model Design / Input

Behavior Models

Sensor Network Internal Mappings

Sensor/Action Models

Sensor/Imaging Physical Network

Sensor Data

Camera System

Captured Events (video clips w/ sensor data )

Meaningful Narrative Discourse (video )

Assembling of Narrative (video )

Training Data

Feedback

Feedback

Feedback
Sensor Network Devices

- Video/Sensor Database
- Back-end Server
- Imaging Sensor Nodes
- WiFi or Ethernet
- Zigbee
- Wearable Narrative Sensor Nodes
- Audio Sensor
- Wrist Sensor
- Participant

Diagram showing the network connections and devices.
Device Overview

Spinner devices include
- Wrist mounted sensor → gesture- and bio- sensing
- Collar mounted sensor → social signaling and audio analysis/recording
- Camera system

Wearable devices functions and capabilities
- Camera system control
- Sensor data capture for video footage cataloguing
- Multimedia browsing

All devices
- support mesh networking
- Are equipped with a location/orientation system
- Have dedicated DSP processing for real-time classification of event data
Device Details – Camera System

- Deployed to cover entire building (>100 nodes)
- 3MP Camera
- Motorized Panning and Focus
- Dedicated Video DSP/ARM - (TI Davinci chip)
- Real-time Linux OS
- LCD displays what is being captured at all times
- Contains Spinner Gateway/Sensor board (detailed on next slide)
Device Details – Spinner Gateway

Works with or without camera board
Communicates with wearable/mobile devices in mesh network
Serves as reference beacon for location system
Ethernet
Audio system with DSP
AVR32
Environmental Sensing
Motion
Humidity and Temperature
Light
Infrared Communication and Detection/Proximity
Device Details – Spinner Social Sensor

Wearable on collar or as pin/badge

**Audio system** with DSP for analytics and CD quality recording

**Compass** for orientation

3-axis **Accelerometer**

**IR** communication and line of sight detection/proximity

**Location engine**

Captures social signal and group dynamics
Device Details – Spinner Wrist Sensor

Wrist worn device
3-axis **Accelerometer**
Galvanic Skin Response (**GSR**) Sensor
**Location engine**
**UI** for interacting with network
Stores and plays videos, providing ownership of video to end user
Captures gesture and indications of affective state
Expanded Reality

Not just a pipe
Technology removes boundaries from Real World to allow new content
Contributions

A novel methodology for humans and machines to filter, organize, and understand large streams of video data

A new form of entertainment and communication that allows you to create media with your social and personal behavior

Toolkit for documentation of daily life that may lead to new and unexpected insights about random events

These capabilities could lead to a new form of online community
The UberBadge

Mediate Group Interaction & Behavior Modeling

- 16-bit MCU w/ 64kb flash, 2k RAM, and GCC support
- 45-LED Display intended to be read at distance
- IR communications
- RF communications with second processor to handle MAC
- Up to 256MB of data memory
- Audio input and output with onboard microphone
- Onboard accelerometer
- Pager motor for vibratory feedback
- Multiple ports for expansion
  - Accepts Sensor Stack Modules
- Optional LCD display

Mat Laibowitz
Responsive Environments Group
Broadcast Messages

Information on your badge is mainly for other people, **not you!**
Audience Voting in Auditorium

- Red = No, Green = Yes

Chart showing:
- Yes: 63%
- No: 37%
Parasitic Mobility
Responsive Environments Group

To request more info on this demo:

Aim badge at the hot-spot
Do you see a green Light?

Press either button on the badge.

Orange and Red Light?
The request is noted.

The UbER-Badge Demo Hot-Spot
Bookmark data posted on website

Joseph Branc

Sponsors you interacted with:

- Michael Caine
- Frank Graziano
- Kiyoshi Kunii
- Jay Lee
- Akinori Matsuo
- Paul Moody
- Joel Stanfield
- Makoto Takashima
- Saeko Tezuka
- Funio Ueno
- Steve Whittaker
- Muneharu Yoshida
- Peter Wakim

Projects you have expressed interest in tracking:

- Treehouse Studio
- Moving Portraits
- Attentive Devices
- Object Awareness
- Plunge n’ Play
- SandScape
- The FindIT Flashlight
- Audiopad

Note: You can make private or company-specific annotations to the projects by editing this page. If you’d like to make public annotations to the projects, please enter the discussion on the project page in pedia.media.
Bookmark data posted on website

Stephan Guttowski

Sponsors you interacted with:

- Christine Kallmayer (Fraunhofer IZM)
- Torsten Linz (Fraunhofer IZM)

Projects you have expressed interest in tracking:

- Affective-Cognitive Learning and Decision-Making Affective Computing (http://www.media.mit.edu/~hiahn)
- Conversation Table, Stealing Table Computing Culture (lira\@mit.edu)
- Negotiation Dynamics Human Dynamics (http://groupmedia.mit.edu)
- How to Make Almost Anything, Almost Anywhere Physics and Media Group (http://fab.cba.mit.edu)
- Tangible BPA Tangible Media (http://tangible.media.mit.edu/projects/tbpa/)

Note: You can make private or company-specific annotations to the projects by editing this page. If you'd like to make public annotations to the projects, please enter the discussion on the project page in pedia.media. Badge data you may previously have had on this page can be viewed in the page history below.
Badge Accelerometer & Audio Data

Accelerometers

Audio (Difference) Signals For All Badges During 7/5/05

Microphone
Auditorium Fidgeting

- Medium-good correlation with length of talk
- “Resets” with every presentation
**Interest Meter & Group Dynamics**

**Badge-Badge**

Badge-to-Badge Classifications for 'Interested' Encounters

- **Interested**
- **Uninterested**

Classification Value = \( f(\text{voice, motion, face-face time...}) \)

**Badge-Demo**

Badge-to-Demo Classifications for 'Interested' Encounters

- **Interested**

80% Accuracy

Collaboration with Human Dynamics Group
Affiliated Wearers

Affiliated people tend to spend more time face-face and move together!

Accuracy of inferred affiliation: 93%
Affiliated Wearers from Energy Only
Timekeeping for Talks

Out of time!!

- 24 talks in the morning (research updates)
- 5 Minute time limit on each!
- Audience badges flashed time queues
- We didn’t run over (first time ever…!!)
Smart pendants to Amulets

Band-pass Filter Bank
- 300 Hz – 4000 Hz
- 300 Hz – 570 Hz
- 570 Hz – 1090 Hz
- 1090 Hz – 2000 Hz
- 2000 Hz – 4000 Hz

Microphone → Pre-Amplifier → Comparator

Microcontroller → ADC → DAC

Microcontroller → Bluetooth Radio

USB Rechargeable LiION Battery

Memory → 2.4 GHz Radio Transceiver

PCB Front View:
- microSD card socket
- MEMs Microphone
- IrDA Transceiver

PCB Back View:
- 3-axis Accelerometer
- 2.4 GHz Radio

ARM Microcontroller

Expansion Port

Bluetooth Module

minUSB port

Analog Band-pass Filter Bank

Li-ion Battery Connector

Speaker

Push Button

Slide Switch
Conclusions

• Sensing, computation, and communication become tightly integrated and commonly embedded
• Low power and energy scavenging enable active nodes to be embedded and “forgotten”
• The Ubicomp infrastructure permeates our cities, our dwellings, our objects, our clothing, and eventually our bodies
  – Pervasive-Wearable-Implantable
• The 5 human senses locked into our body are augmented by interfaces into ubiquitous sensor network data
  – Marshall McLuhan for real
  – Interface devices now - implantables some day
  – Omniscience…
• This infrastructure mediates everything
  – Collaboration, business, social interaction…
  – Context engines filter, represent, and manifest information
    • Google for reality
• Brave New World
  – Privacy, security, promises vs. perils…