Building Pervasive Computing Environments - Pervasive 2007 Tutorial

Prof. Joseph A. Paradiso - MIT Media Lab - Cambridge MA, USA
Expanded for CSIM Lecture #2
This talk is online at:

• http://www.media.mit.edu/~joep/Outgoing/Pervasive-2007-Tutorial.ppt
What are the components of “Pervasive Computing” Environments?

- Sensors!!
- Signal Conditioning Electronics
- Power Conditioning Electronics
- Microcontrollers
- Wireless Hardware
- Embedded Software
- Communications Software
- Networking Protocols
- Inference/Context Engines
- Application Software
MAS 836

Sensor Technologies for Interactive Environments
Joseph Paradiso (joep@media.mit.edu)

Credit Hours: 0-12-0

This class will explore sensor technologies for smart environments and interactive applications; giving students a broad introduction to state-of-the-art techniques, exposure to current research, and practical experience that will assist in developing and fielding such systems in their own work. We will introduce the principles and operation of many sensor families and discuss applications in computer-human interfaces, new musical instruments, medicine, environmental sensing, ubiquitous computing, and other current areas of interest.

Topics will include:

- Basic signal conditioning electronics for standard sensor systems
- Pressure and force sensing
- Piezoelectrics and related materials
- Electric field sensing and inductive techniques
- Optical sensing
- Thermal and acoustic sensing
- RF and microwave systems
- Inertial and orientation sensing
- Macroparticle, chemical, and environmental systems
- Medical and radiation sensing
- Digital sensor modules and emerging interface standards

See www.media.mit.edu/resenv/classes.html for more information

Weekly readings will be assigned - class will involve problem sets and a final project

Class will meet Tuesday mornings, 9 AM-12 PM in E15-054

Class size limited - Permission of instructor required
(email jwood@media.mit.edu)

http://www.media.mit.edu/resenv/classes.html
Reference Sources

- Jacob Fraden
  - AIP Handbook of Modern Sensors, >2’nd Edition
- Ramon Pallas-Areny and John G. Webster
  - Sensors and Signal Conditioning, 2’nd Edition
- Thomas Petruzzellis
  - The Alarm, Sensor, & Security Cookbook (others!)
Auxiliary References (signal processing)

- Ramon Pallas-Areny & John G. Webster
  - Analog Signal Processing
- Paul Horowitz & Winifield Hill
  - The Art of Electronics
- Don Lancaster
  - Active Filter Cookbook
Auxiliary References

• Walt Jung
  – The OpAmp Cookbook
• John Brignell & Neil White
  – Intelligent Sensor Systems
• H.R. Everett
  – Sensors for Mobile Robots
Good Niche References

- Larry Baxter
  - Capacitive Sensors
- APC International
  - Piezoelectric Ceramics: Principles & Applications
- Bioelectric books - Webster, Norman
- MSI & Piezo Systems online guides
- Melles-Griot Optics Guide (free!)

(No biosensors in this tutorial)
Magazines

• Sensors Magazine - Free!
• Circuit Cellar - Best EE-hacker magazine out

Also basic electronics-hacker-entry-level books, like “Physical Computing: Sensing and Controlling the Physical World with Computers,” by Tom Igoe & Dan O'Sullivan
Websites

- **http://www.sensorsportal.com/**
  - References, hints, sources
- **http://www.sensorsmag.com/**
  - Sensors Magazine site
    - Buyers guide, Archive articles
- **http://www.cs.cmu.edu/~chuck/robotpg/robofaq/10.html**
  - Robotics sites often list sensor vendors, hints
- **http://www.billbuxton.com/InputSources.html**
  - Bill Buxton’s encyclopedia on input devices
Basic Sources for Electronics

Digikey - www.digikey.com
Mouser - www.mouser.com
Newark
Allied
Hosfelt Electronics
JameCo
Mat Electronics
JDR
All Electronics
Radio Shack (mainly online now)
Position Encoders

- **Displacement**
  - Rotary or Linear Potentiometer
  - Linear encoder
    - Optical
    - Magneto-Acoustic
  - Shaft encoders
    - Rotary into Linear w. screw

![Image of potentiometer and encoder components](image)

**FIGURE 5.34.** Incremental (A) and absolute (B) optical encoding disks.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interface</td>
<td>CANopen</td>
</tr>
<tr>
<td>Resolution/Revolution</td>
<td>16 Bit = 65,536 steps</td>
</tr>
<tr>
<td>Revolutions</td>
<td>up to 14 Bit = 16,384</td>
</tr>
<tr>
<td>Code</td>
<td>Binary</td>
</tr>
<tr>
<td>Housing Diameter</td>
<td>56 mm</td>
</tr>
<tr>
<td>Shaft</td>
<td>Full shaft 6 or 10 mm a / hollow shaft 15 mm a</td>
</tr>
</tbody>
</table>
Quadrature Encoders Determine Direction

2 emitters

2 photodetectors

Holes at 90° and different r

Rotating Disk

2 Holes and 1 dual optical sensor

One sensor measures “I” and the other measures “Q”

-> Direction determined by whether I leads Q in time or vice-versa

1 hole and 2 single optical sensors
Pressure

• Displacement into pressure
  – E.g., \( F = -kx \), and \( P = F/A \) (force per area)

• Strain into pressure
  – Strain is defined by \( s = \Delta L/L \)

• Piezoresistivity
Membrane Switch

Fig. 9.3. Membrane switch as a tactile sensor.

- Commercial – can be printed and snap-assembled
  - Made by ALPS among others (switch floor too)
  - Typically polled in row-column fashion (e.g., drive columns, read rows)
How a MIDI Keyboard Works

- **Velocity**
  - Measure time difference between key transitions

- **Aftertouch**
  - FSR underneath keys
    - FSRs were developed for this purpose (Interlink)
  - Poly aftertouch has FSR under each key
  - Mono aftertouch has FSR under key bank
Conductive Foam

Standard (3D!)

Metalized
Resistive (conductive) Elastomers

Early Z-Tiles from the University of Limerick


- Carbon or silver-loaded silicone rubber
- Dynamic range limits, hysteresis, longevity…
- Commercial conductive rubber from:
  – “Zoflex” from Xilor, inc. (rfmicrolink.com)

Force Sensitive Resistors

- Composite structure
  - Top, ink, electrodes
  - Flat, but can be fragile to shear force (delamination) and sensitive to bend
Conductive Polymers and FSR’s

- Microphotograph, showing conductive ink and metalization from Interlink FSR

For a resistive polymer Velostat™ (from 3M), of thickness 70 μm and a specific resistance of 11 kΩ/cm², resistance for pressures over 16 kPa can be approximated by

\[ R = \frac{51.93}{p^{1.47}} + 19. \]
FSR Characteristics

• 3-4 decades of sensitivity, 0.01 - 100 PSI, hundreds of Ω to 10 Meg Ω
  – Depending on device & Manufacturer
  – “---” is part-part repeatability bound
    • Typically ±15% - ±25% for Interlink
  – Sensitive to temperature, humidity...

*(Interlink Datasheet)*
FSR Interface Circuits

- **Voltage Divider**
  - Very nonlinear; switch characteristic
  - Only buffer needed

- **Current Mode**
  - Better dynamic range
  - Transimpedance amp

(Interlink Datasheet)
Many Shapes and Sizes

Various options from Interlink

**The FSR Potentiometer**

Can also inject voltage into W and have transimpedance amplifiers at A and B. Position is:

\[
\frac{(V_A - V_B)}{(V_A + V_B)}
\]

and Force becomes:

\[
V_A + V_B
\]

Oscillator

Ratiometric? From Rob Poor?
The FlexiForce (from TekScan)

Performance

- Linearity (Error) < ±5%
- Repeatability < ±2.5% F.S.
- Hysteresis < 4.5% F.S.
- Drift < 3%/Logarithmic Time
- Rise Time < 20 μsec

Typical Sensor Response

![Graph showing typical sensor response with force in lbs on the x-axis and V_out (V) on the y-axis.]

Typical Response

- Force Ranges
  - 1 lb. (4.4 N)
  - 25 lb. (110 N)
  - 100 lb. (440 N)
  - 500 lb. (2200 N)
  - 1000 lb. (4400 N)
Other Players - TekScan - FSR imaging matrices

Figure 1. Smart Skin Structure
# Tekscan Specs

| Table 1. Specifications of Representative Tactile Sensors | Robustness? |
|---|---|---|
| | Human Skin [i] | Fingerprint Imaging Sensor [vii] | Smart Skin |
| Resolution (mm) | 2 | 0.1 | 0.1-10 |
| Sensor Area (mm²) | 25x25 | 13x20 | $10^2$–$10^7$ |
| Number of Sensels | $10^2$ | ~$10^4$ | $10^2$–$10^6$ |
| Sensel Force Range (N) | 0.4-10 | switch | 0.05-100 |
| Linearity | Moderate | - | High |
| Hysteresis | Low | - | Very Low |
| Compliance | Yes | No | Yes |
| Bandwidth (Hz) | 100 | ~10 | 100 |
| Operating Temperature (°C) | -20 to 60 | -10 to 45 | -40 to 100 |

Force Imaging

Car driving over force imaging plate

Figure 3. Pressure image of a tire

Figure 5. Pressure image of a human hand. The scale on the colorbar represents the amount of force in arbitrary units.

They do chair seats and beds too...

Hong Tan, Purdue

Figure 4. Ordinary pressure distribution of feet
**QTC Pressure Sensors**

- **Made by Peratech in the UK**
- **Quantum Tunneling Composites**
  - Metal-filled polymers, no direct conductive path
    - Current flows via quantum tunneling (AC readout w. capacitance?)
    - More tunneling (hence current) with more pressure
    - No zero-point deadband, smoother response, (durability??)
  - Many form factors (buttons, cables, etc.)

---

### Specifications

<table>
<thead>
<tr>
<th>Specifications</th>
<th>QSRC0250S0</th>
<th>QSRC025130</th>
<th>QSSC025400</th>
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<tbody>
<tr>
<td><strong>Dimensions</strong></td>
<td></td>
<td></td>
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<tr>
<td>Form Factor</td>
<td>Circular</td>
<td>Circular</td>
<td>Square</td>
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<tr>
<td>Active Area</td>
<td>8mm</td>
<td>13mm</td>
<td>40mm</td>
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<tr>
<td>Lead Length</td>
<td>35mm</td>
<td>35mm</td>
<td>35mm</td>
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<tr>
<td>Thickness</td>
<td>1mm</td>
<td>1mm</td>
<td>1mm</td>
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<tr>
<td><strong>Electrical</strong></td>
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<td></td>
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<tr>
<td>Stand-off resistance</td>
<td>$10^8$ ohms</td>
<td>$10^8$ ohms</td>
<td>$10^8$ ohms</td>
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<tr>
<td>Force sensitivity range</td>
<td>0 N - 100 N</td>
<td>0 N - 100 N</td>
<td>0 N - 100 N</td>
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<tr>
<td>Part-to-part force repeatability</td>
<td>±10%</td>
<td>±10%</td>
<td>±10%</td>
</tr>
<tr>
<td>Single part force repeatability</td>
<td>±2%</td>
<td>±2%</td>
<td>±2%</td>
</tr>
<tr>
<td>Force resolution</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Max current</td>
<td>100μA/cm²</td>
<td>100μA/cm²</td>
<td>100μA/cm²</td>
</tr>
<tr>
<td><strong>Environmental</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-30°C to 100°C</td>
<td>-30°C to 100°C</td>
<td>-30°C to 100°C</td>
</tr>
<tr>
<td>Humidity</td>
<td>0% - 100%</td>
<td>0% - 100%</td>
<td>0% - 100%</td>
</tr>
<tr>
<td>Lifetime</td>
<td>&gt; 1M cycles at 10N</td>
<td>&gt; 1M cycles at 10N</td>
<td>&gt; 1M cycles at 10N</td>
</tr>
</tbody>
</table>

1. Unloaded, unburnt
2. Depend on mechanics
3. With repeatable actuation system

---

**Sensing Performance**

- **Resistance vs Force**

![Graph showing resistance vs force for QTC Pressure Sensors]
Sensor Net Array, Kapton Embedded (SNAKE) Skin

- All on flex
- Embedded strain gauges
- Covered by a layer of QTC pressure measuring material
- Piezo whiskers
- Optical sensors, microphones, temperature
- Peer-Peer network
- High-Speed I²C backbone
- Scalable!

Jerry Barroeta-Perez
FSR Bendy Sensors

The Flex Sensor is a unique component that changes resistance when bent. An unflexed sensor has a nominal resistance of 10,000 ohms (10 K). As the flex sensor is bent the resistance gradually increases. When the sensor is bent at 90 degrees its resistance will range between 30-40 K ohms.

The sensor measures 1/4 inch wide, 4 1/2 inches long and only .019 inches thick!

Available from the Images Co. (for PowerGlove - made by “Abrams-Gentile”)

High-end versions made by Immersion for their CyberGlove
- 0.5° resolution, 1° repeatability, 0.6% max nonlinearity, 2-cm min bend radius

*These only measure bend in one dimension (expanding the FSR’s on surface)*
- Conduction saturates quickly when contracted
- Can measure bidirectional bend with 2 FSR’s back-to-back (and diff amp)
Some FSR-Bendy-Sensor Gloves

Mattel’s Power Glove
1989

Laetitia Sonami’s Lady’s Glove
(STEIM, 1997)

Immersion’s Cyber Glove

The 22-sensor CyberGlove has three flexion sensors per finger, four abduction sensors, a palm-arch sensor, and sensors to measure flexion and abduction. Each sensor is extremely thin and flexible being virtually undetectable in the lightweight elastic glove.
Recognizing Upper Body Postures using Textile Strain Sensors  
Corinne Mattmann, Oliver Amft, Holger Harms, Gerhard Tröster, and Frank Clemens (ETH Zurich) - Proc. Of ISWC 2007

“A novel strain sensor was used which was developed by EMPA, Switzerland [12]. The sensor thread consists of a commercial thermoplastic elastomer (TPE) filled with 50wt-% carbon black powder and changes resistivity with length. It is fiber-shaped with a diameter of 0.3mm and has, therefore, the potential to be fully integrated into textile. In this prototype setup, the sensor was attached with a silicone film (see Fig. 2) which enables a measurement range of 100% strain. The length of the sensor was chosen to be 2cm.”

TMS International - breathing belts (resistive)  
http://www.tmsi.com

More on fabric-compatible sensors in Bio Lecture...
Merlin Stretch Sensors...

Commercial stretchy resistive sensor

Merlin Stretch Sensor

The Merlin Stretch Sensor uses the latest 'Smart' material technology to give a uniquely flexible sensor, that can literally take measurements bent around corners or be woven into fabric.

- Flexible sensor, bends around corners!
- Small form factor - 2mm Cord
- Economical

What is it?
The Stretch Sensor is a flexible cylindrical cord with spade electrical fixings at each end. The sensor behaves like a variable resistor, the more you stretch it the higher the resistance.

How does it work?
As the length of the Stretch Sensor alters so does it's resistance. For each centimeter of length change there is a resistance change of approximatly 400 Ohms/cm.

http://www.merlinrobotics.co.uk
Strain Gauges

A wire strain gauge is composed of a resistor bonded with an elastic carrier (backing). The backing, in turn, is applied to the object for which stress or force should be measured. Obviously, that strain from the object must be reliably coupled to the gauge wire, whereas the wire must be electrically isolated from the object. The coefficient of thermal expansion of the backing should be matched to that of the wire. Many metals can be used to fabricate strain gauges. The most common materials are alloys \textit{constantan}, \textit{nichrome}, \textit{advance}, and \textit{karma}. Typical resistances vary from 100 $\Omega$ to several thousand ohms. To possess good sensitivity, the sensor should have long longitudinal and short transverse segments (Fig. 9.2), so that transverse sensitivity is no more than a couple of percent of the longitudinal. The gauges may be arranged in many ways to measure strains in different axes. Typically, they are connected into Wheatstone bridge circuits (Section 5.7 of Chapter 5). It should be noted that semiconductive strain gauges are quite sensitive to temperature variations. Therefore, interface circuits or the gauges must contain temperature-compensating networks.

\textit{Many manufacturers (e.g., JP Technologies), many patterns...}
Strain Gauges want to be bonded onto a hard surface, so they can be forced into strain when the surface is deflected. Soft materials won’t strain the gauge enough
Diana Young’s wireless bow

- Strain gauges on bow for bow bend (in x,y) and twist.
- Accelerometers for 3-axis motion
- Capacitive transmitters as before for position

Load Cells

- Bond strain gauge to cantilevered beam
  - Force deflects beam, bends strain gauge, creates signal
- Can be quite accurate
  - Compensate temperature effects

Simple, “naked” load cell from Ohio State

20 Ton load cell for truck weight

Load Cell assortment from DHS
Pressure Sensors

Hydraulic Load Cell

Many manufacturers: Motorola, MSI, Silicon Designs...

• Absolute and Differential (air or fluid) pressure
  – Back of diaphragm open or closed to the air/medium
By looking at the dynamic pressure balance on the table, objects on the table can be identified by weight change and tracked by force balance. Ditto for people moving around the floor.

*Albrecht Schmidt, et al., Ubicomp 2002*
Piezoelectrics

Measure dynamic force

Ferroelectrics

- Deformation of unit cell produce charge
  - Crystals (Barite), Ceramics (PZT), Polymers (PVDF)

- Crystal lattice gives intrinsic polarization
- Ceramics, Polymers need to be polarized
  - E fields, pulling, Temp (7 C above)

- For to become "semi-cooperative low polymer"
Piezo Axes under Strain

Exploit 3-1 Mode!!

Note: Connected here in parallel for power generation
Piezo Foil (PVDF)

http://www.meas-spec.com/myMeas/sensors/piezo.asp
I tend to use high-impedance amplifiers for piezoelectric elements

Some use charge-sensitive (integrating or transimpedance) amplifiers - e.g., to approximate steady-state pressure
The Disposable Wireless Sensors

• Very simple 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
CargoNet: A Low-Cost MicroPower Sensor Node 
Exploiting Quasi-Passive Wakeup for Adaptive 
Asynchronous Monitoring of Exceptional Events

• Suite of sensors includes tilt, vibration, shock, sound, humidity, temperature, tamper, light
• Dynamically programmable quasi-passive wakeup on shock, sound, RF, light change
  – Can adapt to environments with persistent stimuli
  – Abnormal conditions stored to flash memory along with time stamp: know what happened when
  – Wake on RF interrogation
• Small and inexpensive
• Microampere current draw: years on a single coin cell battery
PVDF strip laminated onto balloon surface forms speaker and microphone
- Simple electronics enable very simple “behavior”
- All over Media Lab for 10’th birthday (60 made)
The Magic Carpet

- Foot position, dynamic pressure captured by 4” grid of piezoelectric wire
- Pair of orthogonal Doppler radars measure upper body motion
- Not currently in the Brain Opera...
Sensing in the Carpet

- Up to 64 PVDF wires are sampled at 60 Hz
- MIDI note events generated at every peak
- Simple electronics...
Carpet Data Analysis

Raw data from carpet wires

Data after time clustering

Wires along "x" axis

Wire Number

Elapsed Time (sec)

Step

Stomp

Radius $\propto$ Pressure

Wires along "y" axis

Radius $\propto$ Pressure

Step

Stomp
Noncontact Gesture Sensing

- User must contact transmitter
- User uniquely tagged
- Can use multiple frequencies; multiple users
- 2-object geometry
  => Best for accurate tracking
- Industrial (short range) proximity

- No contact with electrode
- 3-object geometry
  => Hard to do tracking
- Can “focus” w. tomography
  => Add more transceivers

Loading Mode (measure $I_t$)

- Single Electrode
- No cable to electrode
- Couples to everything
- Hard to adjust sens. area
- Used for everything
  - Stud finders (pre MIR)
  - Theremins, buttons...

Equivalent circuit for all modes of electric field sensing

- Transmit mode ($C_t \gg C_g$)
- Shunt mode ($C_g \gg C_t$)

$V_{out} \propto i_r$

Transconductance Amplifier (FISH front end)
Cello Bow Sensors - 1990

Transmit antenna capacitively couples into bow electrode

\[ f_t \approx 100 \text{ khz} \]
\[ \lambda \approx 2 \text{ miles} \]

\[ y = f(V_L + V_R) \]
\[ x \propto V_L - V_R \]
Wireless Violin Bow Sensors - 1993

50 kHz
XR-L555

6.2 Volt Battery

100 kHz
XR-L555

Resistive Strip

Capacitive Coupling

Hand Grounding Strip

Receive antenna on violin bridge

JFET Source follower (on violin)

Coax to signal conditioner

Bow Left = Signal at 50 kHz
Bow Right = Signal at 100 kHz

Common (Room) Ground
Performance Debuts

Yo-yo Ma; August 14, 1991
Tanglewood

Ani Kavafian; September, 1993
St. Paul, MN
The PAN Handshake - 1995
The Penn and Teller Spirit Chair - 1994

Legend:
A: Copper plate on chair top to transmit 70 kHz carrier signal
B: Four illuminated antennas to sense hand positions
C: Two antennas to detect left and right feet
D: Two pushbuttons for generating sensor-independent triggers
E: Digital display for computer to cue performer
F: Four lights under chair platform, nominally controlled by foot sensors

Transmit Mode
Debut at Digital Expression, Kresge Auditorium MIT

Media Medium

October, 1994

Showtime!!
Harmonix spun off - 1995

The 2008 TIME 100

Artists & Entertainers

Alex Rigopulos & Eran Egozy
By Steven Van Zandt

The record business is over! there's no new rock 'n' roll on the radio! Kids couldn't care less about music! Quick, somebody call Alex and Eran. Yes, I mean Alex Rigopulos, 38, and Eran Egozy, 36, the Batman and Robin of Harmonix,

Eran Egozy (mapping software for chair)
Alex Rigopulos (joystick music)
The Former Prince

Wembley March '95

Dual shunt-mode frame

Shunt-mode Mannequin
Minimal Capacitive loading circuit

- Pin 1 is digital output, pin 2 is digital input
- Toggle state of pin 1 and measure time needed for state of pin 2 to flip
  - Time difference increases with R and C
    - Fix R, hence C is measured
- Loading mode measurement – range typically few cm
Rehmi Post’s E-Field Touch Table

No hand present

Hand present

tauFish array with 30 tauFish (120 electrodes)

Loading Mode
Used at MOMA, 1999

Finger  Palm
Switched Capacitor Measurements

\[ \text{Charge Pump!} \]

\[ V_s = \frac{V_r \cdot C_x}{C_s + C_x} \]

\[ C_x = \frac{V_s}{V_r} \]

Measure \( V_s \), infer \( C_x \)

Close/open \( S_3 \) - Discharge \( C_s \)

Close \( S_1 \) → Charge \( C_x \)
Open \( S_1 \)
Close \( S_2 \) → \( C_x \) charge goes to \( C_s \)
Repeat \( N \) times

Measure \( V_{C_s} \)

\[ \text{Next Measurement} \]

**Charge Pump Capacitive Sensing**

- Sensitive down to 0.01 pF (10 Attofarads)!
- Short switching times involved (e.g., 100 nsec)
  - Not much background at these frequencies
    - And not much time for interference to integrate
  - Repeated pulses can be intrinsically spread spectrum
    - Irregular intervals don’t correlate with artificial sources
      - Noise is intrinsically integrated out
  - Can “see” through water??
    - Water has resistance, fast pulses don’t engage intrinsic RC highpass

\[ \tau = R_w C_w \]

Switching happens here
Simple Induced-Hum Touch Sensor

- 50/60 Hz pickup couples into high-Z input
  - Triggers logic high
  - Can use essentially any Hi-Z (e.g., CMOS) gate
  - Static protection??

Touch switch.

Touch Keyboard on EMS Synthi AKS
The Motorola MC33794 chip

- Newly developed for SeatSentry with ML
- Leveraging into many other applications
- 9 channels
Family of capacitive sensors from AD

- AD7142 (14-channel) and several others
- T/R mode
- Calibrates out external signals when sensors idle
- Low power - aimed at touch controllers and sensors (e.g., humidity)
- SPI output

http://www.analog.com/en/content/0%2C2886%2C760%255F788%255F66102%2C00.html
# Magnetic Field Sensors

## Table 1. Magnetic Sensor Technology Field Ranges

<table>
<thead>
<tr>
<th>Magnetic Sensor Technology</th>
<th>DETECTABLE FIELD RANGE (gauss)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQUID</td>
<td>10^{-8} 10^{-4} 10^{0} 10^{4} 10^{8}</td>
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<tr>
<td>FIBER-OPTIC</td>
<td></td>
</tr>
<tr>
<td>OPTICALLY PUMPED</td>
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<tr>
<td>NUCLEAR PRECESSION</td>
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<tr>
<td>SEARCH-COIL</td>
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<tr>
<td>ANISOTROPIC MAGNETORESISTIVE</td>
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<td>FLUX GATE</td>
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<td>MAGNETOTRANSISTOR</td>
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<td>MAGNETODIODE</td>
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<td>MAGETO-OPTICAL SENSOR</td>
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<td>GIANT MAGNETORESISTIVE</td>
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<tr>
<td>HALL-EFFECT SENSOR</td>
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</tr>
</tbody>
</table>

*Note: 1 gauss = 10^{-4} tesla = 10^{5} gamma*
Hall Sensors

Magnetic Field Sensors

DC Field

- Hall Sensor

Work for strong magnets out to several cm.

Allegro - www.allegromicro.com

\[ \vec{F}_L = -e\vec{V} \times \vec{B} \]

Package UA, 3-pin SIP

1. VCC
2. GND
3. VOUT
Many Varieties...

Hall-Effect Sensor Selection Guides

- **Current Sensor Modules** (ACS750SCA-050, ACS750LCA-050, ACS750SCA-075, ACS750LCA-075, ACS750SCA-100, ACS750ECA-100)
  The ACS750 is the latest in innovative, integrated solutions from Allegro MicroSystems and the first step in a new revolutionary line of fully-integrated in-circuit current sensors. This unique current-sensing assembly includes a high-current conductor, magnetic concentrator, and an optimized monolithic Hall IC in a convenient and compact package.

- **Unipolar Hall-Effect Digital Switches** (3121, 3122, 3123, 3141, 3142, 3143, 3144, 3240)
  The unipolar Hall-effect switch is characterized by the magnetic operate threshold (Bop). If the Hall cell is exposed to a magnetic field from the south pole greater than the operate threshold, the output transistor is switched on; by dropping below the threshold (Brp), the transistor is switched off.

- **Micropower Omnipolar Hall-Effect Digital Switches** (3212, 3213, 3214)
  Unlike other Hall-effect switches these devices switch on with the presence of either a north or south magnetic field that has sufficient strength; in the absence of a magnetic field the output is off. These switches have a lower supply voltage range as well (2.5 V to 3.5 V) and a sample period generated by a unique clocking scheme to reduce power requirements.

- **Bipolar Hall-Effect Digital Switches** (3132, 3133, 3134, 3425)
  The bipolar Hall-effect switches generally switch on with a south pole of sufficient strength and switch off with a north pole of sufficient strength however the output state is not defined if the magnetic field is removed. To ensure the device switches an opposing magnetic field of sufficient strength should be used.

- **Hall-Effect Switches for Two Wire Applications** (1140, 1142, 1143, 1145, 1180, 1181, 1182, 1183, 1184, 1161, 1163, 1165, 1186, 1187, 1189, 3250, 3255, 3257, 3285)
  The output signal for Hall-effect switches for two wire applications is based on their current consumption.

- **Programmable Hall-Effect Switches** (3250, 3251)
  The programmable Hall-effect switch sensor can be programmed to the desired magnetic operate switch point.

- **Latching Hall-Effect Digital Switches** (3175, 3177, 3185, 3187, 3188, 3189, 3275, 3280, 3281, 3283)
  The latching Hall-effect switches will always switch on with a south magnetic of sufficient strength and switch off with a north magnetic field of sufficient strength. The output will not change if the magnetic field is removed.

- **Linear Hall-Effect Sensors** (1321, 1322, 1323, 3503, 3515, 3516, 3517, 3518)
  The linear Hall-effect sensors voltage output accurately tracks the changes in magnetic flux density.

- **Dual-Output Hall-Effect Digital Switches** (3275)
  The dual-output Hall-effect device features two outputs which are independently activated by magnetic fields of opposite polarity.

- **Gear-Tooth/Ring-Magnet (Dual Element) Hall-Effect Sensors** (ATS610LSA, ATS611LSB, ATS612LSB, ATS612LSG, ATS622LSB, ATS625LSG, ATS643LSH, ATS645LSH-I1, ATS645LSH-I2, ATS660LSB, ATS665LSG, ATS671LS, ATS672LSB-LN)
  The gear-tooth/ring-magnet Hall-effect sensors are monolithic integrated circuits that are designed switch in response to differential magnetic fields created by ferrous targets.

- **Adaptive Threshold Sensor Modules** (ATS610LSA, ATS611LSB, ATS612LSB, ATS612LSG, ATS622LSB, ATS625LSG, ATS643LSH, ATS645LSH-I1, ATS645LSH-I2, ATS660LSB, ATS665LSG, ATS671LS, ATS672LSB-LN)
  The adaptive threshold sensors are smart sensors that learn about their targets to optimize the magnetic circuit detection. Each module combines in a compact high-temperature plastic package, a samarium-cobalt magnet, a pole piece, and a Hall-effect IC that has learning capability. These sensors can be easily used in conjunction with a wide variety of gear or target shapes and sizes.
Packages and integrated sensors

ANALOG DEVICES

Hall sensor package
Linear Output
Magnetic Field Sensor

AD22151

FEATURES
- Adjustable Offset to Unipolar or Bipolar Operation
- Low Offset Drift over Temperature Range
- Gain Adjustable over Wide Range
- Low Gain Drift over Temperature Range
- Adjustable First Order Temperature Compensation
- Ratiometric to \( V_{CC} \)

APPLICATIONS
- Automotive
  - Throttle Position Sensing
  - Pedal Position Sensing
  - Suspension Position Sensing
  - Valve Position Sensing
- Industrial
  - Absolute Position Sensing
  - Proximity Sensing

FUNCTIONAL BLOCK DIAGRAM
Permalloy

- Permalloy Sensors
  - Magnetically sensitive resistance
  - Philips KYZ series
  - Honeywell (HMC)

- Very sensitive (Compass!!)
- Low R bridge (200k) - High current
- Permalloy can demagnetize - **Differential strapping for compasses**

*HMC2003 Magnetic Hybrid*

+-2 Gauss max range
Compasses...

Compass needle Angle sensed with Hall sensors

Vector 2X

Dinsmore

HMR3100

DIGITAL COMPASS SOLUTION

Features
- 5° Heading Accuracy, 0.5° Resolution
- 2-axis Capability
- Small Size (13mm x 13mm x 4.5mm), Light Weight
- Advanced Hard Iron Calibration Routine for Stray Fields and Ferrous Objects
- 0° to 70°C Operating Temperature Range
- 2.8 to 5 volt DC Single Supply Operation

General Description
The Honeywell HMR3100 is a low cost, two-axis electronic compassing solution used to derive heading output. Honeywell’s magnetoresistive sensors are utilized to provide the reliability and accuracy of these small, solid state compass designs. The HMR3100 communicates through binary data and ASCII characters at four selectable baud rates of 2400, 4800, 9600, or 18000. This compass solution is easily integrated into systems using a simple UART interface.

Figure 5: The KVH C-100 Fluxgate Compass. Courtesy of KVH [2].
Digital 3-axis tilt-compensated compass

3-Axis Compass with Algorithms

HMC6343  Honeywell

The Honeywell HMC6343 is a fully integrated compass module that includes firmware for heading computation and calibration for magnetic distortions. The module combines 3-axis magneto-resistive sensors and 3-axis MEMS accelerometers, analog and digital support circuits, microprocessor and algorithms required for heading computation. By combining the sensor elements, processing electronics, and firmware into a 9.0mm by 9.0mm by 1.9mm LCC package, Honeywell offers a complete, ready to use tilt-compensated electronic compass. This provides design engineers with the simplest solution to integrate high volume, cost effective compasses into binoculars, cameras, night vision optics, laser ranger finders, antenna positioning, and other industrial compassing applications.

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Beat frequency metal detector

Metal Detector

Loading mode

Inductive "Thermal"

Wireless "boot" coil and AM radio

\[ \frac{1}{\tau c} \]

\[ L_0 C \frac{1}{\tau c} \]

\[ C = \frac{1}{2\pi f_0} \]

\[ \frac{1}{2\pi f_0 \sqrt{N_1 N_2}} \]
Active Magnetic Tracking

MOMA Installation, 1/01

Workspheres

Collaboration with Maeda group

Rough basis of devices from Polhemis, Ascension
Smart, Passive Objects

- ID, sensors in passive objects remotely interrogated
  - Tangible bits with no batteries, wires, line-of-sight!
Swept-Frequency Tag Reader

- Looks for magnetically-coupled resonant loads from 50-300 KHz
- Early EAS systems, “Grid-Dip Meter”
- Simple, cheap, fast, but limited range
Early (1995) ML Lego Demo

Tags Present

Tags Absent

- Pickup coil under LEGO platform
  - Drive frequency swept 40 - 300 kHz
  - Resonant loading detected => tag identified
Multiple modes of control

*Increase read range and # objects*

*Now 20 tags in system and 16 objects*

- Wearable Ring tags
  - Continuous control on each finger (no glove)
- Tags that sit in reader area
  - Set background, context…
- 3-axis tags (respond to orientation and range)
  - Can be rolled around or manipulated
- Local sensor tags
  - Respond to pressure (or pull, etc.) and displacement

*Many degrees of control...*
Tagged Objects

Resonant Frequency is “ID”
Pick L,C or cut resonant strip
Actual Baseline - Antilog Sweep

- **400 Khz**
- **50 Khz**

**No Tags**

**Pumpkin Only**

**Red Ring, Block Face, Dinosaur**

**All Rings, Goblin, Corn, Dinosaur**
Tag Proximity Sensing
Tag Angle Sensing

Integrated Tag Peaks vs. Rotation Angle

Reconstructed Absolute Angle vs. Rotation Angle
Tag Pressure Sensing

Pez Controller Extended

Pez Controller Contracted

Tag Peaks as Pez is Pulled

Peak Timing vs. Pez Displacement

Coil wound around outside of Pez’s body
Swept Tags as a Musical Controller

Inspired by John Zorn’s early Performances
Tag tracking and sensing

SMAU Convention, Milan, October 2000

EMP Seattle, April 2001

Volumetric Tag Tracking

Advanced Musical Mappings – Demo!
Musical Navigatrix

Laurel (Pardue) Smith’s Meng, 2001

- Multicoil tracking (Olympics)
- X,Y,Z sensitivity
- Can lock tag response w. switch
- Control musical parameters at high level (sequences, timbres)
- Can record, overdub actions
Multiaxis tag tracker
Accelerometers:
- Tilt Switches

- Effectively a threshold on a single angle (with respect to gravity), tilt switch draw virtually no power and are excellent for simple motion detection

Mechanical tilt switches can also be spring-mounted for higher acceleration thresholds

- Mercury tilt switch
  - Connection between two pins made or broken by bubble of mercury
- Pinball tilt switch
  - Cross between mercury tilt switch and inclinometer

ALPS SPSF100100
SMT version of “ball in cup”

3-axis “Ball in Cup”
Accelerometer switches and piezo cantilevers

- Acceleration switch
  - e.g., proof-mass reed, ball in magnetic can (old airbag sensors!)
  - Made by many companies

- Piezoelectric Cantilevers
  - Made by MSI
The Wireless Jerk Sensors

- Very simple motion sensor
  - Cantilevered PVDF piezo strip with proof mass
  - Activates CMOS dual monostable when jerked
  - Sends brief (50 µs) pulse of 300 MHz RF
  - Glued into a tube for simple handheld use
Accelerometers:  
Piezoelectric - Circuitry

Also have digital versions

Multiaxis Shock Sensors
Piezoelectric Ceramic Sensors (PIEZOTITE®)

Miniature Piezoceramic Accelerometers

Shock Sensors

The shock sensor, PKGS series, is an acceleration sensor with 2 terminals and detects acceleration & shock to be applied from outside, as electrical signal. By bimorph piezo elements clamped at the two-end with original polarization technology, the shock sensor has high sensitivity and excellent durability. The shock sensor is reflow solderable SMD type. The shock sensor can have inclined primary axis so that appropriate shock sensor can be chosen for shock detection in HDD (Hard Disk Drive) and optical pick-up control in optical drive & optical-magnetic Drive.

- Features
  1. Small size, low profile, high sensitivity and excellent durability.
  2. Excellent linearity.
  3. High resonance frequency and wide bandwidth.
  5. Reflowable.
  6. In addition to the voltage sensitivity type shock sensor (ME, LB and LC series), new type, the electrical charge sensitivity type shock sensor (NB, MF and LD series) are released. NB, MF and LD series have better anti-reflow temperature.

- Applications
  1. HDD data writing protection, while shock is applied from outside.
  2. Shock detection and protection in DVD, CD-R, CD-RW etc.
  3. Pick-up control for disk type storage in Digital camera, Camcorder etc.
  4. Other applications requiring acceleration detection.
Accelerometers: ADXL202

- ADXL202 from Analog Devices (2 axis)
  - Range: ±2g
  - Size: 5mm x 5 mm x 2 mm
  - Bandwidth: 5 kHz
  - Noise: 4.3mg (@50Hz)
  - Cost: $10

- Duty-cycle output for easy interfacing
ADXL330 - 3-axis accelerometer

Specifications

- Typical Band Width (kHz): 1.6kHz
- Voltage Supply (V): 2.0 to 3.6
- Range: +/- 3.6g
- Sensitivity: 300 mV/g
- # of Axes: 3
- Sensitivity Accuracy (%): Â±10
- Package: 4mm x 4mm LFCSPP
- Supply Current: 0.2mA
- Noise Density (Âµg/rtHz): 280

Single proof mass for all 3 axes
ST single-chip 3-axis accelerometers

Figure 1 LIS3L02AS ELECTRICAL CONNECTION

Figure 2. Block Diagram LIS3L02DQ

Analog Outs

Digital Output

VDD

LIS3L02AS

Ground

100µF 10µF

VDD

FS

ST

PD

X

Z

1

Y

Vout X

Vout Y

Vout Z
3-Axis accelerometers from others...

Kionix KXM52

Freescale MMA7260Q
Accelerometers: Thermal

- A heated bubble of air can also act as a proof mass.
- Its shifts with acceleration can be detected by a quadrant of temperature sensors – giving a two-axis system.
- MXR7202GL from MEMSIC (2 axis)
  - Range: ±2g
  - Size: 5mm x 5 mm x 2 mm
  - Bandwidth: 20 Hz
  - Noise: 1.3mg (@20Hz)
  - Cost: $3
  - Pin for pin same as ADXL202
Gyroscopes: Murata ENC03J

- ENC03J from Murata (1 axis)
  - Range: ±300°/sec
  - Size: 0.6in x 0.3in x 0.2in
  - Bandwidth: 50 Hz
  - Noise: 0.5°/sec (@50 Hz)
  - Cost: $40
**Gyroscopes: Analog Devices ADXRS300**

- **ADXRS300 from Analog Devices (1 axis)**
  - Range: $\pm 300^\circ/\text{sec}$ (can bias for 40 x this range)
  - Size: 7mm x 7mm x3mm
  - Bandwidth: 40 Hz
  - Noise: $0.6^\circ/\text{sec}$ (@40 Hz)
  - Cost: $33
IDG 300 and IDG 1000 series
Dual axis gyroos from InvenSense

It’s a race - 2 axis, 3 axis gyroos then integrated IMUs
Red Sox Spring Training - March 2006

Biomotion measurement of a Red Sox Pitcher

Modified sensors for high range and high sample rates

- 1kHz sampling with data logged to flash memory
- Torso - Single IMU with 10g accelerometer, 1500 deg/sec gyro
- Upper Arm - Double IMU
  - 10g accel, 1500 deg/sec gyro
  - 70g accel (ADXL78), 10000 deg/sec gyro
- Wrist - Double IMU
  - 10g accel, 1500 deg/sec gyro
  - 120g accel (ADXL193), 10000 deg/sec gyro
- Hand - Single IMU with 120g accelerometer, 10000 deg/sec gyro
Preliminary Results - Red Sox Spring Training

- 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
- Hand-soldered BGA’s failed!
Photoresistors

CdS tends to like Yellow...
Photons knock electrons into conduction band
1 photon can release 900 electrons
Acceptor band keeps electron lifetime high
-> Lower Resistance with increasing light
Slow response...

- CdS (Cadmium Sulfide) and CdSe (Cadmium Selenide) cells are common

( I ) Directly beneath the conduction band of the CdS crystal is a donor level and there is an acceptor level above the valence band. In darkness, the electrons and holes in each level are almost crammed in place in the crystal and the photoconductor is at high resistance.

( II ) When light illuminates the CdS crystal and is absorbed by the crystal, the electrons in the valence band are excited into the conduction band. This creates pairs of free holes in the valence band and free electrons in the conduction band, increasing the conductance.

( III ) Furthermore, near the valence band is a separate acceptor level that can capture free electrons only with difficulty, but captures free holes easily. This lowers the recombination probability of the electrons and holes and increases the number for electrons in the conduction band for N-type conductance.

Condition like FSR’s (voltage divider, transimpedance amp, etc.)
Photodiodes

Photons interacting in the depletion region produce electron-hole pairs

- Electrons diffuse through depletion region, driven by the E-field, to arrive at the N layer and electrode, producing current.
- Depletion region bigger (more reverse bias)
  - More efficient (higher probability of photon interaction)
  - Faster (charge doesn’t have to diffuse across longer lengths before it hits E-field, hence less charge stored, hence smaller capacitance)
  - PIN diodes increase the collection area - faster response
Silicon has more than 2x response in IR
Reverse bias lowers capacitance (makes device faster, extends sensitivity)
Photodiode IC’s

**OPT211**

**MONOLITHIC PHOTODIODE AND AMPLIFIER**

**FEATURES**

- **WIDE BANDWIDTH, HIGH RESPONSIVITY:**
  - $R_n$ Bandwidth
  - 1MHz: 50kHz $^*$
  - 100MHz: 5kHz $^*$
  - 1kHz $^*$
  - *with bootstrap buffer

- **PHOTODIODE SIZE:** 0.090 x 0.090 inch (2.29 x 2.29mm)
- **HIGH RESPONSIVITY:** 0.45A/W (650nm)
- **LOW DARK ERRORS:** 2mV max
- **EXCELLENT SPECTRAL RESPONSE**
- **LOW QUIESCENT CURRENT:** 400μA
- **TRANSPARENT 8-PIN DIP**

**APPLICATIONS**

- MEDICAL INSTRUMENTATION
- LABORATORY INSTRUMENTATION
- POSITION AND PROXIMITY SENSORS
- PHOTOGRAPHIC ANALYZERS
- BARCODE SCANNERS
- SMOKE DETECTORS

**DESCRIPTION**

The OPT211 is a monolithic photodiode with on-chip FET-input transimpedance amplifier, that provides wide bandwidth at very high gains. Uncommitted input and feedback nodes allow a variety of feedback options for maximum versatility. Trade-offs in responsivity (gain), bandwidth and SNR can easily be made.

The monolithic combination of photodiode and transimpedance amplifier on a single chip eliminates the problems commonly encountered in discrete designs such as leakage current errors, noise pickup and gain peaking due to stray capacitance. The 0.09 x 0.09 inch photodiode is operated at zero bias for excellent linearity and low dark current. Direct access to the detector’s anode allows photodiode bootstrapping, which increases speed performance.

The OPT211 operates over a wide supply range (±2.25V to ±18V) and supply current is only 400μA. It is packaged in a transparent plastic 8-pin DIP specified for the 0°C to 70°C temperature range.

![Spectral Responsivity Graph](image-url)
Color Sensors

Color Light Sensor - Avago ADJD-S371-Q999

Features:
• 10 bit per channel resolution
• Independent gain selection for each channel
• Wide sensitivity: 0.1k - 100k lux
• Two wire serial communication
• Built in oscillator/selectable external clock
• Low power mode (sleep mode)
• Integrated solution with sensor, LED and separator in module for ease of design
Like diodes, all transistors are light-sensitive. Phototransistors are designed specifically to take advantage of this fact. The most-common variant is an NPN bipolar transistor with an exposed base region. Here, light striking the base replaces what would ordinarily be voltage applied to the base -- so, a phototransistor amplifies variations in the light striking it. Note that phototransistors may or may not have a base lead (if they do, the base lead allows you to bias the phototransistor's light response).

Phototransistors run in the photoconductive mode.

They’re pretty slow, on average (e.g., Khz response)

…But give a fair amount of gain and are very easy to use.

– Generally ground emitter and provide a collector resistor to set gain

Photodarlingtons give more gain, but can be slower…

http://encyclobeamia.solarbotics.net/articles/phototransistor.html
Dual and Quad Cell Arrays

- Difference over sum gives position
- Limited dynamic range
  - Need to see signal on all of the cells
- Defocus can increase range by making spot bigger
Lateral Effect Photodiodes

Also called "photopots" - photoelectrons create current that divides in proportion to position
- Made by UDT, Hamamatsu, etc.
- Somewhat expensive...

Figure 1.6 With the lateral photodiode, internal resistance forms a current divider that separates $i_p$ into two components whose magnitudes reflect the position of an incident light beam.

Figure 1.10 A duo-lateral photodiode makes both diode surfaces perform lateral current division with two electrode pairs placed for $X$ and $Y$ position indications.

Figure 1.12 A tetra-lateral photodiode places two electrode pairs on the top surface for two-dimensional position sensing without the need for segmented bottom contacts.

CIRCUIT FOR SC SERIES POSITION SENSORS
The “Digital Baton” System

Joe Paradiso, Theresa Marrin, Maggie Orth, Chris Verplatse, Kai-Yuh Hsiao

- Multimodal sensing
  - 5 FSR’s for hand/fingers
    - Thumb, index finger, middle finger, last 2 fingers, palm
  - 3-axis accelerometers (ADXL05) for beats, large gesture
  - 2-axis Optical tracking of baton tip position
    - Synchronous PSD camera sees only tip LED
      - Fast tracking, insensitive to any background light
The Physical Baton

- Potted FSR's
- IR LED

Accelerometers

IR Tracker

Finger Pressure
CMOS and CCD Imagers

VVL (Edinburg pioneers in CMOS cameras)

Photocurrent integrated, then put into transfer register

CMOS Imager - Image charge transferred to transport bucket-brigade register
CCD Imager - Charge moved across continuous substrate
CID array - wire on each photodiode attached to big multiplexer
Cameras on a Chip

- In tiny packages with embedded lenses (and even zoom), typical VGA or better resolution for cellphone cameras
  - Many makers (Sony, ST, Agilent, etc.)
- Different kinds of imagers
  - CID’s, CCD’s, photodiode arrays
    - Line arrays, matrices, etc.
  - Embedded ADC
    - Analog storage, not digital!
    - Beware of dark signal in late pixels for slow readout.
Nintendo Wii Batons

- 3-Axis accelerometer, IR pointer, buttons, expansion
  - Like our baton, but optical part is reversed (camera on Wii)
  - An explosion of musical apps
    - Kyma interface (and many many others)
  - See also famous Johnny Lee Wii “hacking” videos
    - IEEE Pervasive Computing Summer 2008 article
    - Not musical, but informative
Triangulation

Figure 1. An active triangulation sensor measures the distance to a reflecting surface along a projected IR beam by imaging the illuminated area on a position-sensing detector (PSD). The dimension labeled $y$ indicates the position of the focused spot and is inversely proportional to the object distance, $x$.

$$y = \frac{sx_i}{x}$$

where:
- $x$ = the distance to the object
- $s$ = the triangle base
- $x_i$ = the image distance behind the principal point

- $y = s \frac{x_i}{x} = f \sin(\alpha) / x$
  - $y$ is imager coordinate (e.g., readout displacement)
  - $f$ is focal length of the lens
  - $x$ is range of the object

- Asymptotic - tuned for short ranges
- Use synchronous demodulation, lateral effect photodiode
Commercial Devices

- Sharp rangefinder modules - used for toilet flushers, etc.
- Direct digital output of range
- Models optimized to different ranges
  - (e.g., Sharp GP2D12 – 0-80 cm, GP2Y0A2YK – 20-150 cm)
**Pyroelectric Motion Detectors**

Fresnel lens collapses lens to planar structure
- Index of refraction steps discretized
Lens is thinner - less absorption of deep IR
- Polystyrine, etc.
Another is:
442-3 IR-EYE
or:
PYD 1998

Fig. 8-10  Pyroelectric sensor tuna-can mount.  (from Petruzelis)
Thermistors

\[ R = R_0 e^{-\beta \left( \frac{1}{T} - \frac{1}{T_0} \right)} \]

- Thermistors are temperature-sensitive resistors
  - Compensate thermal effects in analog circuits...
- Metal Oxide Thermistors have NTC
- Much more sensitive than RTD
  - Goes from -8% to -2% per °C
  - NTC worse for self-heating, runaway problems
    - Depends on airflow…
- Can make PTC thermistors
  - Polycrystalline ceramic (Barium or Strontium Titanate)
  - PTC sensitivity can get to 200% per °C
    - Narrower range…

Thermistors can age (chip packaged can degrade at +1% per yr, glass beads much slower)
Semiconductor Junctions

\[ I_c = I_0 e^{\frac{qV_{BE}}{2kT}} \]

- Every transistor is a temperature sensor
- Most thermometer IC’s exploit this
- Many packages available
  - LM35Z from National
  - AD592 from Analog
  - Dallas Digital TMP series
- Often integrated into microcomputers too
  - MSP430, etc. - nearly all microcomputers have them now
Internal vs. External Sensors

Singapore Test Tag #1: Comparison of Temperature Sensors

- MSP430 Integrated Humidity Sensor
- SHT11

CargoNet Tag - Singapore to Taiwan - Malinowski M.Eng.
Humidity Sensors

**Capacitive**

The typical uncertainty of capacitive sensors is ±2% RH from 5% to 95% RH with two-point calibration.

**Resistive**

Many varieties of capacitive humidity sensors

Exponential resistance-to-RH characteristic

Often coat board substrate with polymer.

Temperature compensation needed.

Interdigitated fingers - need AC source

**Thermal**

For measuring absolute humidity at high temperatures, thermal conductivity sensors are often used. They differ in operating principle from resistive and capacitive sensors. Absolute humidity sensors are left and center; thermistor chambers are on the right.

*Other types: Chilled Mirror optical humidity sensor, etc.*

http://www.sensorsmag.com/sensors/article/articleDetail.jsp?id=322590

Denes K. Roveti, July 2001
“Inexpensive” Surface-Mount Humidity Sensor
Sensirion SHT11

2 sensors for relative humidity & temperature
Precise dewpoint calculation possible
Measurement range: 0-100% RH
Absolute RH accuracy: +/- 3% RH
Temp. accuracy: +/- 0.4°C @ 25 °C
Calibrated & digital output (2-wire interface)
Fast response time < 4 sec.
Low power consumption (typ. 30 µW)

5 day test:
- Ship to Pepsi
- Weekend in warehouse
- On delivery truck
- Ship back to MIT

- Surface mount - precise temperature & humidity measured
- Digital connection - readings are compensated
Acoustic Transducers

- Measure dynamic range to moving diaphragm
- Carbon mic
- Condensor mic
- Electret mic
  - Foil electret mic
  - FEP material polarized with corona discharge
  - Wideband
    - $10^{-3}$ Hz to hundreds of MHz
  - Usually have integrated FET
Hooking Up An Electret Mic

Only need resistor and capacitor
**Good Electret Microphones**

**Appearance**

- Sensitivity Range: 
  - $-36 \pm 2$ dB
  - $-38 \pm 2$ dB
  - $-40 \pm 2$ dB
  - $-42 \pm 2$ dB
  - $-44 \pm 2$ dB
  - $-46 \pm 2$ dB

**Dimensional Drawing**

- **EMB465**
- **EMB465P**

**Typical Frequency Response Curve**

- Sensitivity: See above (0dB=1 V/Pa 1kHz)
- Directivity: Omnidirectional
- Impedance: Low impedance
- Current Consumption: Max. 0.5mA
- Standard Operation Voltage: 4.5V
- Sensitivity Reduction: Within-3dB at 1.5V
- SN Ratio: More than 60dB

**Schematic Diagram**

- Sensitivity: Refer to above (0dB=1 V/Pa 1kHz)
- Direction: Omnidirectional
- Impedance: Low impedance
- Current Consumption: Max. 0.5mA
- Standard Operation Voltage: 4.5V
- Sensitivity Reduction: 1.5V=3dB at 1.5V
- SN Ratio: More than 60dB

**Electret Condenser Microphone**

- Part Number: 254-ECM6443-RO
- Dimensions: mm (in.)
- Date: 2/26/09

**Electrical Specifications:**
- Sensitivity: -44±3dB
- Output Impedance: 2.2K (max.)
- Frequency Range: 70-18,000Hz
- Standard Operation Voltage: 2.0V
- Current Consumption: 0.5mA (max.)
- SN Ratio: >58dB

**Mechanical Specifications:**
- Operating temperature: -25°C ~ +70°C
- Storage temperature: -40°C ~ +70°C

**Note:** RoHS Compliant

Available from Mouser Electronics www.mouser.com (800) 346-6873

Specifications are subject to change without notice. No liability or warranty implied by this information. Environmental compliance based on producer documentation.
More Acoustic Transducers

Piezoceramic microphone
- Cheap and sensitive
- Can be peaky (Passive acoustic flattening filters)

Just PZT plate

After mechanical compensation in receiver

Nortel Measurements from cellphone mic
Other Microphones…

- Electrodynamnic Microphones (moving coil)
- Optical microphone techniques
  (spies measuring vibrating windows with laser)

Mic sensitivity measured in dB re. 1 V/µpa
MEMs Microphones

The World’s Smallest Microphone!

- Many Manufacturers
  - Akustica (direct digital output), Infineon, Panasonic, etc.
- Very small - surface-mount chip
- Have integrated amplifier and sometimes ADC
# Knowles SPM0102NE-3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Condition</th>
<th>Limits</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directivity</td>
<td></td>
<td>Omni-directional</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity</td>
<td>S</td>
<td>@ 1kHz (0dB=1V/Pa)</td>
<td>-46 -42 -38 dB</td>
<td></td>
</tr>
<tr>
<td>Output impedance</td>
<td>Z_{out}</td>
<td>@ 1kHz (0dB=1V/Pa)</td>
<td>n/a n/a 100 Ω</td>
<td></td>
</tr>
<tr>
<td>Current Consumption</td>
<td>I_{loss}</td>
<td>across 1.5 to 5.5 volts</td>
<td>0.100 n/a 0.260 mA</td>
<td></td>
</tr>
<tr>
<td>Signal to Noise Ratio</td>
<td>S/N</td>
<td>@ 1kHz (0dB=1V/Pa)</td>
<td>55 59 n/a dB</td>
<td></td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>V_s</td>
<td></td>
<td>1.5 n/a 5.5 V</td>
<td></td>
</tr>
<tr>
<td>Typical Input Referred Noise</td>
<td>ENL</td>
<td>A-weighted</td>
<td>n/a 35 n/a dB A SPL</td>
<td></td>
</tr>
<tr>
<td>Sensitivity Loss across Voltage</td>
<td></td>
<td>Change in sensitivity over 5.5v to 1.5v</td>
<td>No Change Across Voltage Range</td>
<td>dB</td>
</tr>
<tr>
<td>Maximum Input Sound Level</td>
<td></td>
<td>At 100dB SPL, THD &lt; 1%</td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>At 115dB SPL, THD &lt; 10%</td>
<td></td>
<td>dB</td>
</tr>
</tbody>
</table>

**Diagram:**

- Dotted Section Represents Sonic Microphone
  - Term 1
- Term 3
- Term 2
- + Term 4

**Figure:**

- Sensitivity vs Frequency (dB vs Frequency)
Ultrasonic Transceivers

- Electrostatic
- Foil
- High Output
- Lower Q (Bonded)
- So the Polaroid
  - 35 ft.
- Plates

PET

- High Q
- Limited Output
  - Except...
Sonar

RC exponential threshold

$\frac{1}{R^4}$

Reflection or direct

$K_{\text{refl}} e^{-\frac{t}{\tau}}$

$1100 \text{ ft/sec}$

Single RC version

$16\pi^2 R^4$
Sonar Photos...

50 kHz, narrow beamwidth, clicks!

Polaroid electrostatic

Generally 40 kHz, 40°- 80° beam, quiet

Piezoceramic (Murata, Panasonic, APC)
The SRF08

- Available off robotics sites
- Minimal components – uses dual PZT ‘ducers
- Uses TVG
- Claims Range of 6 meters
- Onboard processor – talks via I²C
When the source approaches the observer, the observed frequency is

\[ f_o = \left( \frac{1 - \left( \frac{\nu}{c} \right)}{1 + \left( \frac{\nu}{c} \right)} \right)^{1/2} f_s \]

When the source recedes from the observer, the observed frequency is

\[ f_o = \left( \frac{1 + \left( \frac{\nu}{c} \right)}{1 - \left( \frac{\nu}{c} \right)} \right)^{1/2} f_s \]
Quadrature Doppler Radar Head

- 2.4 GHz CW digital Doppler microwave motion sensor
  - Close relative of microwave intruder detectors
- Low Power (<10 mW)
  - Flat micropatch antenna forms broad beam
  - Sensitive beyond 15 feet
  - Can sense through nonconductive material (walls, etc.)
- *Extremely* inexpensive
  - 1 microwave transistor, 2 hot carrier diodes, etc.

Commercial Doppler & Ranging Radars

From Bill Yerazunis at MERL:

Do you mean the microwave Gunnplexers? Little thing with about an inch of waveguide and then a pyramid-shaped horn with an open bottom?

I usually pick 'em up surplus, but here are good ones:

http://www.advancedreceiver.com/page31.html

They start out at about $250 and work up from there.

Note: keep your eyes open on the surplus / ham radio markets, as I have bought them for as little as ten dollars, including the horn antenna.

Here are some sources (google for "gunnplexer surplus") for Gunnplexers on the cheap:

http://www.hamtv.com/specials.html
http://www.shfmicro.com/unn.htm  (gunnplexers for under $100)

You can also salvage them out of burglar alarms or the gizmos used in supermarkets to automatically open the doors (not the rubber-mat style ones, the ones with a box above the door)

Doppler Motion Radars

From Prabal Dutta at UC Berkeley

We used the TWR-ISM-002 unit from Advantaca (http://www.advantaca.com/).

McEwan Technologies makes UWB/TDR hardware as well:
http://www.getradar.com

Multispectral Solutions makes UWB for localization:
http://www.multispectral.com/

UWB Impulse Radars
Range from Received Amplitude

- Many applications use this (RSSI), but it can vary widely with conditions, people, transmitter/receiver angles, etc.

- If you constrain the system to use state (e.g., where you were before), employ constraints (e.g., you can only go down this corridor from here, and it only goes right, etc.), and use other pieces of information (e.g., multiple RF sources), it can work better (Microsoft RADAR project).

- It’s still not great – you want to use timing (UWB or SS)!

10 meters (coarse zoning), 3 meters (fingerprinting), 1 meter (xmit power step)
# Available RF Modules (1)

<table>
<thead>
<tr>
<th></th>
<th>Aerocomm AC4490-1x1</th>
<th>Chipcon CC1010</th>
<th>Linx Technologies TR-916-SC-S</th>
<th>Maxstream 24XStream</th>
<th>Microchip rPIC12C509AG</th>
<th>Nordic nRF24E1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency Range</strong></td>
<td>902-928 MHz</td>
<td>300-1000 MHz</td>
<td>916.5 MHz</td>
<td>2.4 GHz</td>
<td>310-480 MHz</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td><strong>Methodology</strong></td>
<td>FHSS, FSK</td>
<td>FSK</td>
<td>FSK</td>
<td>FHSS, FSK</td>
<td>OOK, FSK</td>
<td>FSK</td>
</tr>
<tr>
<td><strong>Maximum Bit Rate</strong></td>
<td>115.2 kb/s</td>
<td>76.8 kb/s</td>
<td>33.6 kb/s</td>
<td>20 kb/s</td>
<td>40 kb/s</td>
<td>1000 kb/s</td>
</tr>
<tr>
<td><strong>Standby Power</strong></td>
<td>30 mA</td>
<td>1.3 mA</td>
<td>50 uA</td>
<td>10 uA</td>
<td>0.1 uA</td>
<td>2 uA</td>
</tr>
<tr>
<td><strong>Receiver Power</strong></td>
<td>30 mA</td>
<td>9.1 mA</td>
<td>15 mA</td>
<td>50 mA</td>
<td>N/A</td>
<td>19 mA</td>
</tr>
<tr>
<td><strong>Transmit Power</strong></td>
<td>35 mA @ 2dBM</td>
<td>8.9mA @ -5dBm</td>
<td>29 mA @4dBM</td>
<td>150 mA @ 17dBM</td>
<td>11.5 mA @ 2dBM</td>
<td>10.5mA @ -5dBM</td>
</tr>
<tr>
<td><strong>Receiver Sensitivity</strong></td>
<td>-96 dBm</td>
<td>-107 dBm</td>
<td>-95 dBm</td>
<td>-102 dBm</td>
<td>N/A</td>
<td>-90 dBm</td>
</tr>
<tr>
<td><strong>RSSI Output</strong></td>
<td>N/A</td>
<td>Yes</td>
<td>Yes</td>
<td>N/A</td>
<td>N/A</td>
<td>No</td>
</tr>
<tr>
<td><strong>Package and Size</strong></td>
<td>OEM Module 26mm x 26mm</td>
<td>64TQFP</td>
<td>Module 33mm x 37mm</td>
<td>Module 40mm x 68mm</td>
<td>18SSOP 10mm x 12mm</td>
<td>36QFN 6mm x 6mm</td>
</tr>
<tr>
<td><strong>External Components</strong></td>
<td>None</td>
<td>RX Match, TX Match, VCO Inductor, Crystals for uC</td>
<td>None</td>
<td>None</td>
<td>Crystal for transmitter, Passives</td>
<td>EEPROM for code, Crystal for HCS</td>
</tr>
<tr>
<td><strong>OEM Module Available</strong></td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Comments</strong></td>
<td>Frequency Hopping Spread Spectrum performed by module. Embedded protocol handles headers, acks, rts/cts for streaming data, addressing, error checking.</td>
<td>Integrated 8051, hardware DES, supports frequency hopping, supports two crystals for low power operation</td>
<td>Ready-made keychain remotes and other compatible devices are available</td>
<td>Frequency Hopping Spread Spectrum performed by module. Integrated wire antenna available. Embedded protocol handles acks, retries, and modem-like communications.</td>
<td>Transmitter only – receiver is a separate device, the rfRXD0420</td>
<td>Integrated 8051, power ratings are for RF and don’t include mcu, supports frequency hopping</td>
</tr>
<tr>
<td><strong>Microcontroller Specifications</strong></td>
<td>N/A</td>
<td>8051 based 22 MHz</td>
<td>32kB flash</td>
<td>N/A</td>
<td>N/A</td>
<td>4 MHz 1024 bytes OTP 41 bytes ram WDT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2kB flash</td>
<td>10 bit ADC 2 UARTs SPI, WDT, PWM</td>
<td></td>
<td>16MHz</td>
<td>Requires external flash for program storage 4kB RAM 12 bit ADC SPI, WDT, PWM</td>
</tr>
</tbody>
</table>

## Available RF Modules (2)

<table>
<thead>
<tr>
<th></th>
<th>Radiometrix BIM3</th>
<th>Rayming RE-99, TX-99</th>
<th>RF Monolithics TR1100</th>
<th>RFWaves RFW102-M</th>
<th>Texas Instruments TRF6901</th>
<th>Xemics XE1203</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency Range</strong></td>
<td>869/914 MHz</td>
<td>300 MHz</td>
<td>916.5 MHz</td>
<td>2.4 GHz</td>
<td>860-930MHz</td>
<td>433MHz, 868MHz, and 915MHz</td>
</tr>
<tr>
<td><strong>Methodology</strong></td>
<td>OOK</td>
<td>OOK</td>
<td>OOK</td>
<td>DSSS, OOK</td>
<td>OOK, FSK</td>
<td>FSK</td>
</tr>
<tr>
<td><strong>Maximum Bit Rate</strong></td>
<td>64 kb/s</td>
<td>1.2 kb/s (see comments)</td>
<td>1000 kb/s</td>
<td>1000 kb/s</td>
<td>64 kb/s</td>
<td>152.3 kb/s</td>
</tr>
<tr>
<td><strong>Standby Power</strong></td>
<td>11.5 mA</td>
<td>1.6 mA</td>
<td>0.7 uA</td>
<td>2.6 uA</td>
<td>4 uA</td>
<td>1.10 mA</td>
</tr>
<tr>
<td><strong>Receiver Power</strong></td>
<td>11.5 mA</td>
<td>1.6 mA</td>
<td>8 mA</td>
<td>38 mA</td>
<td>21 mA</td>
<td>17 mA</td>
</tr>
<tr>
<td><strong>Transmit Power</strong></td>
<td>11 mA @ 3dB</td>
<td>1.6 mA</td>
<td>12mA @ 0dB</td>
<td>21mA @ 2dB</td>
<td>40 mA @ 8dB</td>
<td>40mA @ 5dB</td>
</tr>
<tr>
<td><strong>Receiver Sensitivity</strong></td>
<td>-100 dBm</td>
<td>50 ft range guaranteed, 100 ft expected</td>
<td>-87 dBm</td>
<td>-80 dBm</td>
<td>-86 dBm</td>
<td>-100 dBm</td>
</tr>
<tr>
<td><strong>RSSI Output</strong></td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Package and Size</strong></td>
<td>Module 33mm x 23mm</td>
<td>OEM modules 30mm x 60mm</td>
<td>SM-20H 8mm x 11mm</td>
<td>Module 11mm x 16mm</td>
<td>48PQFP 9mm x 9mm</td>
<td>48VQFN 7mm x 7mm</td>
</tr>
<tr>
<td><strong>External Components</strong></td>
<td>None</td>
<td>None</td>
<td>Antenna Filter, Passives</td>
<td>None</td>
<td>Crystal, Antenna Matching Circuitry, Passives (LC Tank circuit)</td>
<td>RX Match, TX Match, VCO Tank, Freq Synth Filter, Crystal</td>
</tr>
<tr>
<td><strong>OEM Module Available</strong></td>
<td>Yes</td>
<td>Yes, only</td>
<td>Yes (dr3000-2)</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Comments</strong></td>
<td>Two versions available for different operating frequencies. Drop-in OEM module. Many other products available from Radiometrix.</td>
<td>Transmitted and Receiver pair. Switch Encoders/Decoders are available. They have several ready made keychain remotes available.</td>
<td>OEM Module is recommended which requires no external components</td>
<td>3 chip solution on module, Built-in DSSS protocol, simple interface to main processor</td>
<td>Simple 3-wire serial interface</td>
<td>Several other chips available.</td>
</tr>
<tr>
<td><strong>Microcontroller Specifications</strong></td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Digital wireless devices are becoming commodity

Leaders:

Chipcon (TI) - 500 kbps radio for ~$1.50 (single qty) and Zigbee radio for ~$5.00 (single qty)

Nordic - 1-4 Mbps radio for ~$5.00 (single qty)

BlueGiga, BlueRadios - Turnkey Bluetooth modules ~$40 (single qty)
Some Sources for Embedded Computer Boards

<table>
<thead>
<tr>
<th>Source</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><a href="http://www.sparkfun.com/">http://www.sparkfun.com/</a></td>
<td>Source for lots of great boards, surplus, &amp; components</td>
</tr>
<tr>
<td><a href="http://www.phidgets.com/">http://www.phidgets.com/</a></td>
<td>Flexible HCI prototyping</td>
</tr>
<tr>
<td><a href="http://infusionsystems.com/">http://infusionsystems.com/</a></td>
<td>The iCube - more for music controllers, but flexible</td>
</tr>
<tr>
<td><a href="http://www.arduino.cc/">http://www.arduino.cc/</a></td>
<td>Prototyping for HCI &amp; interactive art/design</td>
</tr>
<tr>
<td><a href="http://www.parallax.com/">http://www.parallax.com/</a></td>
<td>The BasicStamp - a PIC with native embedded basic</td>
</tr>
</tbody>
</table>

*Also check out Motes (Moteiv, Crossbow), and the boards/systems advertised in Circuit Cellar!*

*But my students tend to build their own boards…*
I was thinking about this, and more or less the only way I recommend experimenting with sensor networks is by building a custom board. I have actually yet to see anything that has really come out of re-purposeable sensor network platforms. Looking through IPSN, any projects that use motes or tinynos are always focused on testing some obscure algorithm and never result in any usable application.

The application based projects or really anything that appears like it could work outside a very narrow domain (like a lab bench) are always built from scratch. The prime example was when Xmal and I went to Intel, they had spent over 10K on a system of motes to try and do what Xmal is doing, and they never got anything to come of it and had to change batteries twice a day. The thing is, building a custom device is not very difficult because all sensor network nodes are very similar. It is a processor, power supply, communication and/or storage, and sensors. Circuitry and code for these systems is easily available and just a matter of selecting the right parts. Then you have to write your application, but you have to do that no matter what platform you us.

That said, the recommendations I have for these systems are:

For power supply circuitry, Texas Instruments is the best. Well, at least they have the best literature making it easy to find a solution. The TI Power Management Selection Guide at http://www.ti.com/litv/pdf/slvt145g is indispensible and has all their chips by application with example circuits. For portable devices, they that the battery specific version of the selection guide: http://www.ti.com/litv/pdf/slym061a 6And this site has uptodate info for portable power: http://focus.ti.com/analog/docs/gencontent.tsp?familyId=64&genContentId=2172

For communication, I only recommend Chipcon. They have plenty of parts for different applications, have great power specs (or at least give you detailed software control of its state for power management), and have decent development tools and kits. Their sample code makes it possible to get a custom protocol running very quickly. www.chipcon.com

For processing, the integrated processors in the chipcon radios are very high-function. They can do almost anything. If you want to move up to a 16-bit processor with ultra-low power usage then you can use the MSP430. The MSP430 has a huge line of parts in many packages, the best power specs with even lower power ones coming out this year. They are 16-bit arch which is very useful. They have DMA which is necessary for low power systems. (so do chipcon integrated CPUs).

In a year, there will be the Chipcon/MSP430 integrated processor which will be the end of even worrying about this. I use the Rowley Crossworks compiler and IDE for the MSP430. It is cheap, only $60 per developer and well-supported. When the MSP430 was new, it was the only choice because the IAR support for MSP430 was pretty poor. But since TI bought IAR, it has become a lot better. But we stick with the Rowley. www.rowley.co.uk

Sensors. I don't really have any favorites here. I just google for the type of sensor i am looking for and see what comes up. After I look in the digikey and mouser catalogs, of course.

Mat now (2009) loves the AVR32 & the CC2480
The Nokia N800 Internet Tablet is an easily hackable hardware (serial port and USB port) and software (Linux-based) handheld device with large touch screen display, Bluetooth, SD, 802.11, web camera, and microphone. It has a very active and supportive development and research community as well.

I agree with Mat's recommendation of the integrated ChipCon radio/microcontroller. The ARM7 chips I'm using are nice and beefy, but relatively complicated. Some of the ARM7 chips from Atmel can even run a micro Linux OS, but I haven't tried that. In terms of compilers and debuggers, I've had good luck with open source tools and bad luck with proprietary tools. Some combination of the GCC tool chain and Eclipse IDE is often available for the popular chips.

I'm using the GCC toolchain for the ARM. I don't like the proprietary IDE I'm using, so don't want to recommend it. In fact, I edit my code in emacs and use the IDE only for downloading and debugging the code. The Silicon Labs chips are good if you need an 8051 compatible controller. In fact, ChipCon might be using them internally on their uC/radio combinations, but I'm not sure about that.

Python is my language of choice for gluing everything together. It runs on the Nokia as well as the desktop. The Python tools I use the most are PyGame (for graphics), numpy and matplotlib (for data crunching and graphing), and pyusb and pyserial for communicating with peripherals.

My operating system of choice is Ubuntu. It's just the easiest thing out there and it has great support. It also plays nicely with Python.

There's lots of potential for using Second Life for pervasive computing experiments. It's still under-appreciated by the research community.
Ari Benbasat (The Stack, MSP430)

Our Stack (http://www.media.mit.edu/resenv/Stack) used the Silicon Labs line of chips. They are pretty nice, running at 25 MIPS and being ridiculously flexible in terms of pin assignment (pretty much any pin can be set to any purpose). They come bundled (in the dev kit) with the Keil C51 compiler, which is easy to use and continuously updated. The eval version is limited to 2K of code, but that is adequate for almost any purpose.

That said, I much prefer the MSP430 series these days. The low power modes are vital to future work, and the SiLabs chips just can't do that adequately. Also, from a sensor-centric point of view, there is no good reason to use a 12-bit ADC with an 8-bit core. It just guarantees that every operation (add/compare/move) is actually three operations which compiled into code. We use the Rowley products in the group, but not one but two big compiler bugs kicked me in the ass while doing the Groggy Wakeup dev, so I am thinking that it is time to give the IAR stuff a shot.

On a vaguely related point, Mat's discussion from before:

> The thing is, building a custom device is not very difficult because all
> sensor network nodes are very similar. It is a processor, power supply,
> communication and/or storage, and sensors. Circuitry and code for these
> systems is easily available and just a matter of selecting the right
> parts. Then you have to write your application, but you have to do that
> no matter what platform you use.

sounds an awful lot like our Stack. There may be room for repurposing it and moving it that direction. There are only really the size issues being a modular prototype and an integrated single-purpose solution. Of course, in wireless networks, that really can make all the difference.
i would agree with mat but just so we dont look like ti sales reps  heres my rfmicro overview from last year (next page)  I’m sure its a bit out of date now

the interesting parts to note other than chipcon is the jennic system  which comes prebuilt  and has a horse of a processor  and a dac

the only missing part is really the sensors  and for cheap off the shelf stuff  sparkfun is the best out there  this is for people who dont want to build all their own stuff

some other points to bring up

parasitic power is not worth the effort at this stage of the game  it doesnt supply enough power  and will constantly get in the way of your application  but if you have to  solar is the only thing with any serious possibility

existing wireless protocols are useless  forget about zigbee  the overhead is way too much for any reasonable system  the only reason to use one of those types of things is for connecting back to a main network hub  in which case you only need one node to have it  and thats wifi or bluetooth  and sparkfun sells those modules as well
### Mark’s RF Selector Chart

<table>
<thead>
<tr>
<th>manufacturer</th>
<th>part number</th>
<th>price @ 1</th>
<th>price @ 100</th>
<th>supplier</th>
<th>transceiver frequency</th>
<th>CPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>chipcon</td>
<td>cc1010</td>
<td>5.49</td>
<td>5.35</td>
<td>mouser</td>
<td>315/433/868/915 MHz</td>
<td>8bit 8051 / 24MHz / 23mA</td>
</tr>
<tr>
<td>chipcon</td>
<td>cc2510</td>
<td>6.49</td>
<td>5</td>
<td>mouser</td>
<td>2.4 GHZ</td>
<td>8bit 8051 / 26MHz / 7.5mA</td>
</tr>
<tr>
<td>jennic</td>
<td>jn5121</td>
<td>15.86</td>
<td>8.6</td>
<td>digikey</td>
<td>2.4 GHZ</td>
<td>32bit RISC / 16MHz / 9mA</td>
</tr>
<tr>
<td>nordic</td>
<td>nrf24e1</td>
<td>4.5</td>
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<td>semiconductorstore.com</td>
<td>2.4 GHZ</td>
<td>8bit 8051 (4 - 20 cycles/instruction) / 20MHz / 3.5mA</td>
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<td>16bit XAP2b / 12MHz / 8.5mA</td>
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### Memory

<table>
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<tr>
<th>Memory</th>
<th>Sleep Current</th>
<th>TX power</th>
<th>RX sensitivity</th>
<th>data rate</th>
<th>lock time</th>
<th>AES</th>
<th>random number</th>
<th>timers</th>
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</thead>
<tbody>
<tr>
<td>32kB Flash / 2kB RAM</td>
<td>34uA</td>
<td>+10dBm / 26.6mA</td>
<td>-107dBm / 11.9mA</td>
<td>76.8kbps</td>
<td>200us</td>
<td>DES</td>
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<td>-100dBm / 12.5mA</td>
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<td>64kB ROM / 96kB RAM</td>
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<td>-90dBm / 19mA</td>
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### UART

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<tr>
<th>uart</th>
<th>adc / conversion time</th>
<th>GPIO</th>
<th>dac</th>
<th>temp sensor</th>
<th>comparator</th>
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<tbody>
<tr>
<td>uart/spi</td>
<td>3 - 10bit / 44us</td>
<td>26</td>
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<td>uart/spi/i2c</td>
<td>8 - 14bit / 1.84ms</td>
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<td>uart/spi/i2c</td>
<td>4 - 12bit / 22us</td>
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<td>2</td>
<td>11bit / 72us</td>
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<td>uart/spi</td>
<td>8 - 12bit / 9.6us</td>
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<td>no</td>
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<tr>
<td>uart/spi</td>
<td>4 - 12bit / 14us</td>
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<td>uart/spi/i2c</td>
<td>7 - 12bit / 4ms</td>
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</table>
hey joe  there really isn't a single opamp that is good for all applications  but there are a few good ones for everything you will do with sensor networks you need a rail to rail as the voltages are too small

the one from the sensors class is the tlv2374  it is very similar to the t1082 except its rail to rail and has lower quiescent current  but its more expensive  its a good choice for starting out as it operates like an ideal opamp for a wide range of inputs and frequencies  and it has extremely low bias current

the lowest quiescent current opamp out there is the tlv2402  which is less than 1uA per amplifier  and there are a number of opamps in this realm  but they tend to have a number of issues  first off  the gbw is usually less than 10khz which make them only useful for buffers  or extremely slow moving signals  they also have high output impedance which can sometimes be a problem if the input impedance to your a to d is too low  and the bias current can be high although there are some with reasonable bias currents  most are on the order of 100pA  which is fine for most things except for piezos

everything else is application specific  a few rules of thumb though if you want higher bandwidth you will need more power or more money you can get better speed by trading off bias current and input common mode voltage  which you can usually make up for with a voltage follower and using inverting opamp configurations you either get low current noise or low voltage noise  but the current noise tends to get higher on lower power opamps same with offset voltage and offset current  at low current the offset voltage is usually pretty good  but the offset current goes to hell  so if you want to build a low power circuit use voltage mode circuits

the opa4379 is almost 1Mhz at 6uA per channel  which is pretty good  so you can get reasonable stuff  but its four times the cost of a low cost opamp like the lpv358  which draws twice as much current for a quarter of the bandwidth  at any rate  you can keep going on like this forever

the other thing to consider is comparators the lowest power is 550na the tlv3402  but again  low slew rate  voltage range on low power stuff tends to be limited as well  usually 5v rails max

switching regulators may not be the best choice for a power supply  for example  if you are using a lithium polymer battery  which charges to 4v and discharges 90% of its power by the time it gets down to 3v  you can get almost the exact same efficiency from a linear regulator as you can from a switching regulator  the differences really dont make it worth the extra rf noise  power supply noise  or component cost and design time

but  the main thing to ask when picking a switching regulator is how much output current will you need  which is why they suck  especially for sensor nodes when you have long periods of low current draw and a few spikes of high current draw  you still need a regulator which can handle the high spikes  which necessarily has a high quiescent current  so for the majority of the time you are throwing away power for the few times you need it  they have a number of dual mode switchers which go into shutdown when they are not sourcing much current  but nothing is perfect

when you operate a switcher in its ideal condition  which is usually near its max output current  you can get 95% efficiency  but drop a few orders of magnitude below that max current  and you're talking 50% efficiency  and if you try to buffer with a large power supply capacitor you effect the switch operation  the frequency shifts and the output tends to come in packets

i dont have any specific recommendations here  again  its very application specific

i know mat uses the bq series battery charger and voltage regulator in one chips from ti  they are handy because they do a lot in a small form factor.