Power and Heat in Ubiquitous Computing

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Challenges

- Power and heat (mips/watt)
- On and off-body networking (bits/joule)
- Privacy
- Interface (additional capability vs. load)
  - User Interface (cognitive load)
  - Ergonomics/human factors (weight, heat, etc.)

(Intertwined – changing one effects the others)

(Starner01 IEEE Micro
“Challenges of Wearable Computing”)
Mobile Computing Trends

(Starner01 IEEE Computer “Thick Clients…” )
Thought Experiment: Distributed AR in San Diego

- Idea: make transponder system, like Metricom, installed by the public on every street sign (“blade”)
- Each street sign transmits information for local intersection and provides simple store-and-forward messaging
- Due to cost of wiring and legal issues, decide not to hook into power grid
Some Numbers

- Expected average battery life: 1 year
- Idle battery life: 10 years
- # street signs in San Diego: 48,000

Problems
- Who replaces batteries?
- When does a battery get replaced?
- 3500 street signs/year for accidents, vandalism, theft, and updates
- Landfill of batteries
Solutions

- Social (government, reward the group, etc.)
- Longer lasting “batteries”
- Scavenge power (Locust)
- Use less power
Energy is the capacity to do work.

- Joule = 1 kg m$^2$/sec$^2$ = 1 Newton of force acting through a distance of 1 meter.

- 1 calorie = 4.19J

- 1 Calorie = 1000 calories

- 1g fat = 9000 cal = 38,000 J

- 1 jelly donut = 330,000 cal = 37g fat
Energy Sources

- AA alkaline battery $10^4$ J
- Camcorder battery $10^5$ J
- Liter of gasoline $10^7$ J
- Daily human diet $10^7$ J
Power

- Power is the time rate of doing work
- \( 1 \text{W} = 1 \text{J/sec} = 1 \text{kg m}^2 / \text{sec}^3 \)
- \( P = IV = I^2R \)  (example, 12V bulb)
- Non standard units of energy: Wsec, Whr, kWhr
- 60 W light bulb for 24 hrs = 1440 Whr = 1.44 kWhr = 5.184MJ
Power Requirements

- Desktop computer (w/o monitor) $10^2W$
- Notebook computer $10W$
- Embedded CPU board $1W$
- Low power microcontroller $10^{-3}W$
- Average human $121W$
## Energy Density

- **Energy per mass (MJ/kg)**
- **Energy per volume (J/cm^3)**

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Energy per Mass (MJ/kg)</th>
<th>Energy per Volume (J/cm^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead acid</td>
<td>0.115</td>
<td>426</td>
</tr>
<tr>
<td>NiCd</td>
<td>0.134</td>
<td>354</td>
</tr>
<tr>
<td>Ni Hydride</td>
<td>0.171</td>
<td>498</td>
</tr>
<tr>
<td>Li ion</td>
<td>0.292</td>
<td>406</td>
</tr>
<tr>
<td>Zinc Air</td>
<td>0.490</td>
<td>571</td>
</tr>
</tbody>
</table>
Getting More Out of Batteries

- Controlled discharge
- Controlled charge
- Temperature
- Fluid flow
Incorporate Recharging into Life Routines

Example for a wearable
- 6 hours – long enough to replace at every meal
- 8-10 hours – replace after work
- 16 hours – recharge when go to bed
Alternative “Batteries”

- Compressed air tanks (5.75 Whr/kg)
- Ultracapacitors (3-30 Whr/kg)
- Fuel cells (548Whr/kg)
- Superflywheel (385Whr/kg)
  - Buckytubes give 10x this amount!

(Michael Johnson aries@media.mit.edu unpublished)
Small Nuclear Sources

- **Material** | **Half Life** | **Energy density**
- Po210      | 0.38 years  | 134W/g
- Pu238      | 87 years    | 0.39W/g

- 6.6% conversion efficiency
- $1500/g Pu238
- Chinese have used Po210 on space program
- Plutonium used in pacemakers (1989)
Environmental Energy Sources

- Solar
- Moving air
- Moving water
- Barometric fluctuations
- Temperature fluctuations
- Cultural electromagnetic noise
- Galactic electromagnetic noise
- Power generation and distribution fields
- Radio and television broadcast stations
- Vibration
Locust: Environmentally Powered Location/Messaging

- PIC microcontroller
- IR xmit/receive
- >6m range
- Location beacon
- Upload location based messages

300 deployed

Next version: AM radio powered

(Starner97 ISWC “The Locust Swarm”)
## Electromagnetic Energy Gleaning

<table>
<thead>
<tr>
<th>Band</th>
<th>W @10% eff.</th>
<th>Field strength v/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM</td>
<td>2.7x10^-4</td>
<td>10^-2</td>
</tr>
<tr>
<td>FM</td>
<td>2.7x10^-9</td>
<td>3.16 x10^-3</td>
</tr>
<tr>
<td>TV2-6</td>
<td>2.2x10^-8</td>
<td>5x10^-3</td>
</tr>
<tr>
<td>TV7-13</td>
<td>4x10^-9</td>
<td>7x10^-3</td>
</tr>
<tr>
<td>TV14-69</td>
<td>9x10^-9</td>
<td>10^-2</td>
</tr>
</tbody>
</table>
Max solar intensity 1000W/m^2
Average 250W/m^2
Max efficiency for solar cells would be 33%, but will not get that
Best two absorbers would be 37-46% eff.
1996 7-17% eff.
2000 (predicted) 10-20%
2010-2020 15-25%
Energy payback in 2-3 years for single crystal silicon
Solar->Electric Conversion

- Direct of photons $350\text{W/m}^2 + \text{indirect sun}$
- Thermal conversion $400\text{W/m}^2$
- Thermal photovoltaic (tpv) $350\text{W/m}^2$ direct
- Fuel drive tpv 20-30%
- Atmospheric conversion – winds
  - $20\text{W/m}^2$ at 5m/sec
  - $160\text{W/m}^2$ at 10m/sec
- Land/sea thermal gradients – small delta $T$
- Atmospheric pressure changes $<4\mu\text{W/liter}$ works underground
Scavenger Robots

- 10kg robot
- Gathers 1kg/hr of combustables
- 10 kWhr/kg
- Does not compete favorably with solar cell
Human Activities

- Sleeping: 81W
- Sitting: 93W
- Conversation: 128W
- Strolling: 163W
- Hiking: 407W
- Sprinting: 1630W
Body-driven power

Body Heat 2.4–4.8 W (Carnot efficiency)

Exhalation 0.40 W (1.0 W)

Breathing band 0.42 W (0.83 W)

Finger motion 0.76–2.1 mW (6.9–19 mW)

Blood pressure 0.57 W (0.93 W)

Arm motion 0.33 W (60 W)

Footfalls 5.0–8.3 W (67 W)

(Starner96 IBM Systems J “Human-Powered Wearable Computing
Shoe Power

(Kymissis98 ISWC “Parasitic Power Harvesting in Shoes”)
Riddle:

What do you call a Pentium-based pocket computer?
Answer

- A soldering iron
Heat

- #1 limiter in current laptop computers (23W)
- Methods of removing heat
  - Convection
  - Conduction
  - Evaporation
  - Radiation
  - Storage
Case Study: Forearm Wearable

(Natural Convection 3.2W)

(Radiation 3.4W)

(Skin Surface Vein)

(Skin Surface Artery)

41.5°C Conduction >13.3W

37°C

(Starner99 MONET “Heat Dissipation…” )
Aside: Science Is Beginning to Look Like Science Fiction

- Science fiction writers are paying attention and provide good scenarios/motivation based on current research!

- Fast Times at Fairmont High (recent Vinge)
- Historical Crisis (Kingsbury) in Far Futures anthology (Benford)
- The Diamond Age, Snowcrash (Stephenson)
- Islands in the Net (Stirling)