Sensornets and the Next Big Thing

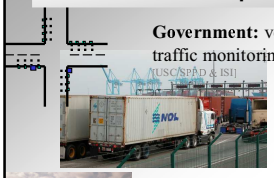
John Heidemann
USC/ISI-Laboratory for Embedded Networked Sensor Experimentation (I-LENSE)
29 January 2007

What Is A Sensor Net?

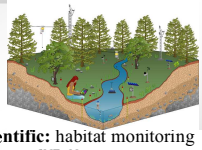
- lots of computers interacting ***within the world***
  - physically distributed, sensing, different perspectives
- ***lots*** of computers interacting within the world
  - enough that they're near what's sensed, 100s-1000s
  - enough that we can loose some and keep going
- lots of ***computers*** interacting within the world
  - intelligent: able to decide what's important, collaborate
- lots of computers ***interacting*** within the world
  - sensing, responding, *acting*

lots of computers interacting within the world

Used for Compelling Applications



Government: vehicle traffic monitoring
[USC/SPAD & ISI]



Scientific: habitat monitoring
[ISI as part of NEON]

Industry: equipment monitoring and control
[ISI and CiSoft]

Military: vehicle tracking
[ISI at DARPA SensIT SITEX]

so, where are we?
(as a research field)

CACM May 2000 "Embedding the Internet"

- special issue editors: Estrin, Govindan, Heidemann
- Proactive Computing, Tennenhouse
  - computers into the world and humans above the loop
- Embedded Computation Meets the World Wide Web, Borriello and Want
  - reviews devices and protocols for an embedded web
- Embedding Robots into the Internet, Sukhatme and Mataric
  - communicating flocks of autonomous, mobile robots
- Amorphous Computing, Abelson, Allen, Coore, Hanson, Homsy, Knight, Nagpal, Rauch, Sussman
  - cellular-level programming models

CACM May 2000 "Embedding the Internet"

- specia nn
- Proact
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- Embe nd Matari
  - con
- Amor Hanson, Homsy
  - cell

themes:

- exploiting Moore's Law to get many small, cheap devices
- getting them into the world
- applying them to interesting problems

pointing at future potential

CACM July **2004** "Wireless Sensor Networks"

- special issue editors: Culler and Hong
- Platforms Enabling WSNs, Hill, Horton, Kling, Krishnamurthy
  - hardware in use: motes to Stargates
- Networking Support for Query Processing in WSNs, Woo, Madden, Govindan
  - directed diffusion, TinyDB
- Security in WSNs, Perrig, Stankovic, Wagner
  - protocols, key exchange, physical security
- Application driven systems research: Habitat Monitoring, Szewczyk, Osterweil, Polastre, Hailton, Mainwaring, Estrin
  - deployments: Great Duck Island and James Reserve

CACM July **2004** "Wireless Sensor Networks"

themes:

• many small, cheap platform *in real use*

• interesting problems in the *real world*

• growing infrastructure *really used outside the lab*

Where are we today?

- huge amount of research
  - routing, distributed algorithms, energy-conserving MACs, operating systems, information processing, storage, actuation and control, programming abstractions, provisioning, deployment
  - localization, time synchronization, clustering, topology control
  - applications: habitat monitoring, precision agriculture, military monitoring, laboratory automation, smart homes and classrooms, geology and seismic monitoring, …
- and significant academic visibility
  - Sensys and IPSN
  - EWSN
  - Emnets
  - IEEE SECON, MASS, RealWSN, SenMetrics, DCSS, INSS,…
  - and related conferences: SIGCOMM, Mobicom, Mobisys, NSDI, SOSP, Mobiquitous, VLDB, SIGMOD, ASPLOS, …
- and industry involvement
  - Intel, Nokia, Sun, …
  - Sensoria, Ember, Moteiv, Crossbow, Arch Rock, Sensorcast, Dust Inc., Mellenium, Ambient Systems, Sownet, ScatterWeb, Adozu…

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overheard at a recent PC meeting

"Do we really need yet another MAC paper?"

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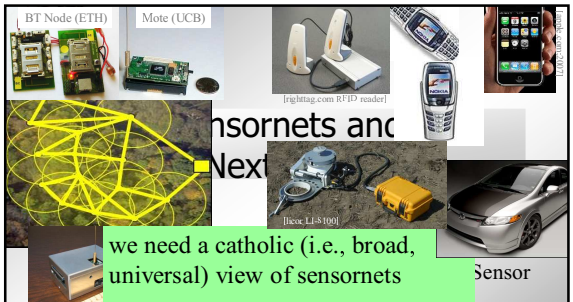
more constructively:

have we solved what we set out to?

did we ask the right questions?



…sornets and …Next …Sensor

we need a catholic (i.e., broad, universal) view of sensornets

lots of interest in BIG things

(and continue developing the core principles)

so, what does a broad view mean?

(what does "sensor network" really mean)

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broaden "***lots***"—big sensors will be more expensive, larger (so not as numerous)

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What Is A Sensor Net?

broaden "***computers***"—not just mote- and Stargate-class computers, but consider bigger (in cars) and smaller (RFID), smarter but narrower (cell phones) and dumber but wider (SCADA)

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broaden "***within the world***"—consider the Internet-side of sensornet data, not just data collection in the field

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what about "lots"?

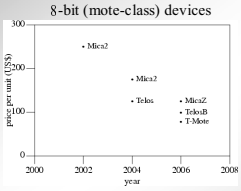
Why "Lots"?

- "Thousands of tiny devices"
- why?
  - to cover the world, near what's sensed (simplify detection)
  - to allow redundancy
  - to exploit short-range radio communication
- research implications
  - need small, cheap devices
  - need an autoconfiguring, self-repairing network
- research results
  - hardware platforms: mote, Mantis nodes, Eyes nodes, BTnodes…
  - self-configuring network protocols and stacks: directed diffusion, MintRoute, TinyDB, many others…
  - collaborative algorithms, localization …

Why Broaden "Lots"?
Much Cheaper is Hard

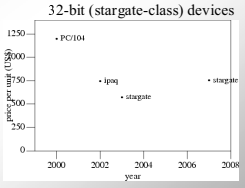
- fixed costs: engineering, packaging, etc.
- to get cheaper, volume has to go *way* up

8-bit (mote-class) devices



no sensors, packaging, quantity 10, academic prices

32-bit (stargate-class) devices



includes wireless network, no sensors, packaging, quantity 10, academic prices

Implication

- expect to see more capability at the $100 price-point (not lower prices)
  - ex: iMote2 $250
  - what do we do with more capability?
    - MB of RAM, Mb/s of comm., standard OSes
- still potential for high-volume application to push many cheap devices
  - but lower cost probably comes with less generality

Why Broaden "Lots"?
Cheap Sensors Are Harder

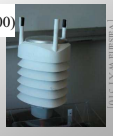
- real-world sensors are not cheap
  - need scientifically relevant suite (more than just temperature and light)
  - need calibration, consistency, longivity
- price for many sensors doesn't track Moore's law
- even when real sensors are cheap(er), other costs
  - mil-spec connectors, cables
  - packaging
  - resupplying


O($10,000)


[Brins MIL-C-24321]

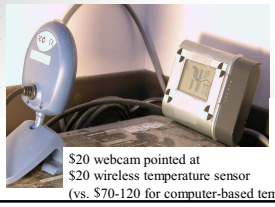

[Sensiron SHT11]
O($1)


[Moog ATS601]
O($100)


[Vaisala WXT510]
O($1000)

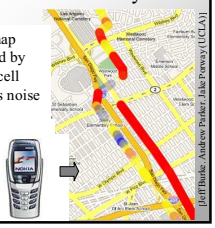
Implications about Sensing

- opportunity for new sensor research
  - new cheap sensors?
  - requires background in many fields (EE, MechE, physics, chemestry, …)
- opportunities to exploit complex and commodity sensors



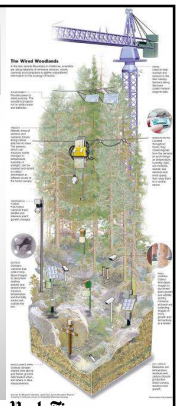
$20 webcam pointed at $20 wireless temperature sensor (vs. $70-120 for computer-based temp)

sound map produced by using a cell phone as noise detector



Implications about Deployments

- more expensive sensors permit more capable hosts
- example: NEON (National Ecological Observatory Network, www.neoninc.org)
  - a "telescope" for biology and ecology
  - an intentionally conservative sensornet design (research is biology, not sensornets)
  - cost of sensors overwhelm cost of hosts
- opportunities:
  - how should we influence the next deployment?
  - what should we learn from their design?



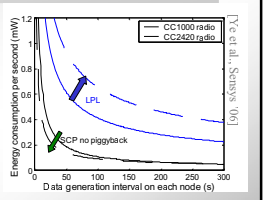
The New York Times 10 May 2005

Why Broaden "Lots"?
One Size Does Not Fit All

- applications are demanding greater capability
  - sophisticated sensors (imagers, audio)
  - greater networking (collaboration and larger data)
- architectures are exploiting tiered systems
  - Tenet (USC & UCLA) mixes motes and Stargates

Implication: Duty Cycling Bigger Devices

- example: duty cycling radios
- two strategies
  - *low-power listening*--wake-up tone (like B-MAC and WiseMAC)
  - *scheduled-channel polling*—coordinate when to listen for tone
- two radios
  - CC1000 (custom): **20kb/s, 1.6nJ/bit** energy-per-second **31mJ/s**
  - new CC2420 (802.15.4): **250kb/s, 0.2nJ/bit** **52mJ/s**
  - new radio is faster and lower energy-per-bit



[Ye et al, Sensys '06]

- with better radio:
  - LPL needs *more* energy: its cost scales with *time on*
  - SCP needs *less* energy: its cost scales with *energy-per-bit*

Other Examples of Duty Cycling Bigger Devices

- tiered radios
  - wake-up radio and data transfer radio
  - described in 2002 (Schurgers et al, Mobicom)
  - implementation with motes and 802.11 (Stathopoulos, INFOCOM 2007)
  - ⇒ CPU power-up time, data size essential
- tiered CPUs
  - early implementations by Pottie and Kaiser (CACM, 2002)
  - ⇒ do wake-up costs scale on bigger CPUs?

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Why "Computers"?

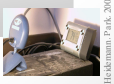
- premise: computation in the network can
  - reduce latency
  - reduce data transfer
  - save energy
- research implications
  - in-network processing
    - aggregation, duplicate suppression, compression, local storage
  - clustering algorithms
  - distributed control and collaboration
- research results
  - IDSQ, pursuer-evader games, …

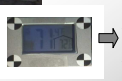
Why Broaden "Computers"?
Raw Data Is Important

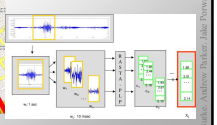
- users want raw data
  - scientists want to re-evaluate, hypothesize
  - industrial SCADA users want central management, long-term trending
- limited opportunity to aggregate anyway
  - if networks are shallower, opportunities for in-network processing are smaller

Implication: Not Just In-Network Processing

- work with scientists to understand when aggregation is acceptable
- logging and storage
  - Capsule, by Mathur et al at Sensys '06
  - Delay Tolerant Networking
- exploiting at-sensor processing
  - image -> temperature
  - sound -> event




74.1 and 72.?

[Hellerstein Hellerstein Peek 2007]

[Jeff Burke, Deborah Estrin, Mark Hansen, Andrew Parker, John Ramanathan, Sasank Reddy, Mani B. Srivastava, Participatory Sensing, UCLA]

Why Broaden "Computers"?
Increasing Involvement

- RFIDs
  - cheap
  - object tagging to simplify identification
- cell phones
  - non-traditional sensors
  - certainly out there today


[rightag.com RFID reader]




[Apple iPhone, 2007]

Implications

- tolerate huge range of "computers"
  - RFID…motes…stargates…PCs in cars
- example work today:
  - Urban Sensing (CENS/UCLA)
  - MetroSense (Columbia and Dartmouth)
  - CarTel (MIT)
  - image-centric sensor networking (Portland State U., Yale, UCLA,…)
  - RFID/Sensornet work (Intel)
  - embedded storage work (HP)

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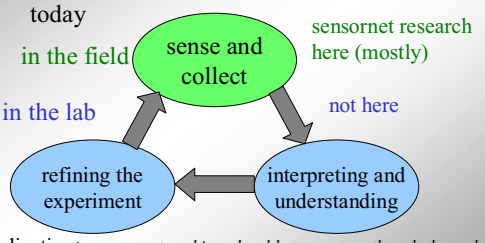
broaden "***within the world***"—consider the Internet-side of sensornet data, not just data collection in the field

Why "In The World"?

- premise:
  - bring computing into the physical world
  - in-situ sensing simplifies sensing
- research implications
  - requires small, cheap, deployable hardware
  - ease of deployment pushes wireless networking
    - some name the field "Wireless Sensor Networking"
- research results
  - lots of good hardware
  - deepening understanding of wireless
  - actual, working deployments

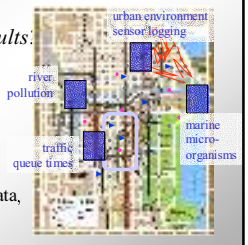
Why Broaden "In The World"?
Complete the Experimental Cycle



Implication: *sensor networking should encompass the whole cycle (in the field* and *in the lab)*

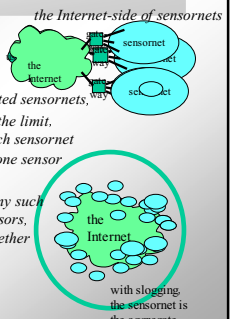
Why Broaden "In The World"?
Shared Sensing

- as sensornets become more numerous
  how do we share data and results:
  - between sensornets
  - between organizations
- Implication: new directions
  - federated sensornets
  - common protocols and tools to exchange data
  - search and discovery sensors, data, trends
  - the *Internet* side of sensornets



Example: Slogging

- what is the limit of "federated sensornets"?
  - each sensornet is one sensor platform
- sensor logging or slogging
  - [term by Mark Hansen]
- many independent sensors become useful in the aggregate



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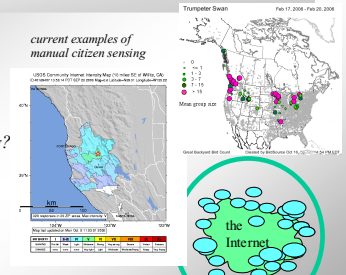
Slogging Implications

- simplify sharing of scientific data
- enable "citizen sensing"
- *can we make shared sensing as easy and common as blogging?*
- other examples of Internet-centric sensornets
  - sensorbase.org (UCLA)
  - CarTel (MIT)
  - SensorWeb (MSR)

current examples of manual citizen sensing



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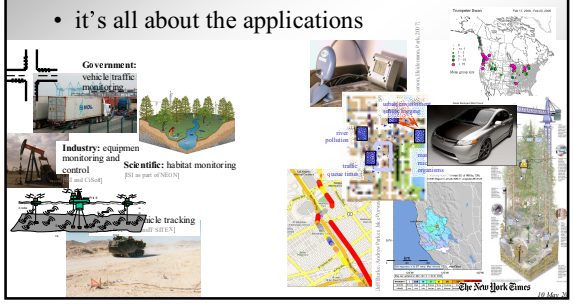
Sensing and Interacting

- sensing and interacting are common thread
- it's all about the applications



Enabling Infrastructure

huge progress in tools and infrastructure:

- systems and services
  - low-memory OSes
  - localization, time synchronization, debugging
  - meta-programming and abstractions
- networking
  - routing protocols
  - energy-conserving MACs
  - topology management and clustering algorithms
- algorithms: information integration and signal processing
- simulators and modeling

…an essential base to build on as we broaden the definition of sensornets

Conclusions

lots of computers interacting within the world

…to me, still defines the core of sensornets

but we need a broader view as well

- "bigger" things, in many dimensions

lots of interesting new work to do…