Emerging networked sensing and actuation technologies: end-to-end wireless systems design for mission critical applications

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Tutorial Goals

- To create awareness of the state of the art in wireless sensor networks (WSN) from technology adoption perspective.
- To explain and demonstrate some of the generic design processes towards development of deployable wireless sensing and actuation systems (system design principles and development life cycle exemplified).
- To provide a live demonstration of a working, application- integrated body sensing and actuation wireless system.

Tutorial pointers

- <u>Timeliness:</u> WSNs are becoming commercial in their simpler forms; also coming out of research labs in elaborate versions;
- <u>Task Difficulty</u>: Designing such systems needs teams of applications specialists, electronics engineers (most often) and definitely Computer Scientists;
- <u>Usefulness</u>: proven, but, apart from being very useful, WSNs are a lot of fun to develop!

Tutorial structure

1. Wireless Sensor Networks (WSN) as enablers for continuous, multi-parameter sensing (20 min, EG)

2. Current “out of the lab” WSN deployments – successes and failures (20min, EG)

3. Research challenges for large scale sensing and actuation (20 min EG)

4. Matching application requirements with available technology – Body sensor network case study (35 min, JB)
   - Application requirements analysis and system overview
   - Wireless sensing system design – components and their role
   - Closing the loop through actuation in wireless systems
   - Results and demonstration

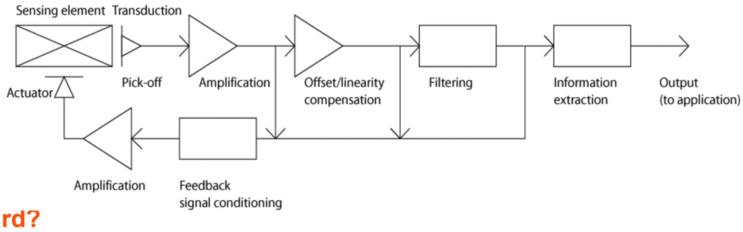
5. Concluding remarks (10 min EG)

Part 1
WSNs as enablers for continuous, multi-parameter sensing

WSN as natural followers from Smart sensing

SS Future directions– many possibilities

- **A/D design boundaries**
- **Ultra-low power/Harsh env.**
- **New apps/new sensors**
- **MEMS/NEMS integration**



- **Systems of sensors – a winning card?**

Multi-sensor systems - wired or wireless

- **particularly networked systems**
- **piggy back on technological advances**
  - **better or**
  - **newly enabled measurement**

Sensor networks

- **rich motivational set**
- **good research niches**

WSNs: research motivation

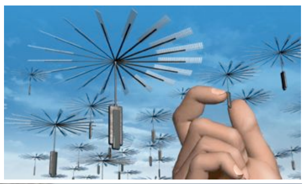
Start point:

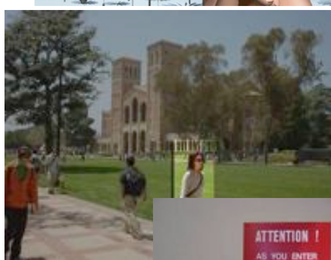
-Smart Dust (1998) – Pister ($35,000) vision of “millions of tiny wireless sensors (motes) which would fit on the head of a pin”

-sharing “intelligent” systems features (self –x) pushed to XLscale – millions of synchronized, networked, collaborative components

Today:

-Dust Networks - $30 mil venture (2006);
-TinyOS – the choice for 10000 developers
-make the news and popular press
- fashion accessory & easy lobbying
- big spenders have committed already (BP, Honeywell, IBM, HP)
-technologies matured (digital, wireless, sensors)
-first working prototypes;
-getting towards “out of the lab”
-social scientists are getting ready!





Attention! Your spatio-temporal activities are recoded and analyzed by the 20000 sensors wide campus net

Dreams- …imagine….

"They've been igniting people's imaginations."

"It's kind of like the beginning of the Arpanet days for this sensor-net technology, where there's no killer app yet" (PARC)

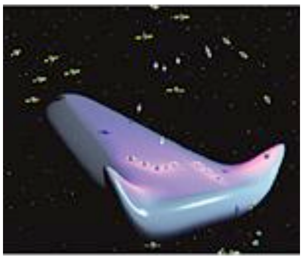
"Once you wrap your brain around the concept—that the physical world can become a computing platform—any number of consumer and research applications come to mind."

"But they've served as a placeholder people can use to envision applications with the understanding that they'll be replaced by better technology"

"At current prices, though, minus the sensors attached to them, wireless motes are still impractical for most large networks"

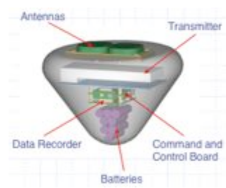
Hundreds of "dreamed of…" application scenarios have been produced to date– some very pretty, all very useful!!!

Some such Dreams

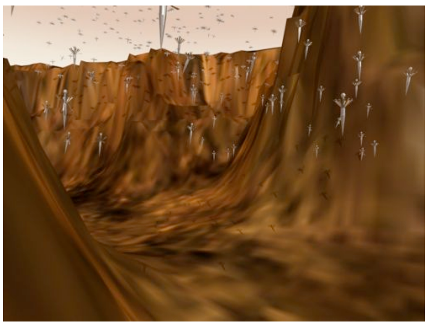


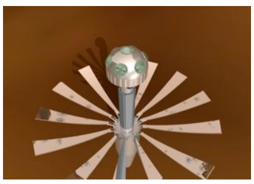
Dream extension of 'Robust Aerospace Vehicle'
The Vision: Brilliant structural systems that do not age or fail

ENSCO and Berkeley University for NASA
The Vision: "micron-scale" airborne probes that can take measurements over all regions of the Earth with unprecedented spatial and temporal resolution



NASA
The vision: Micro Spacecraft to Pave the Way for Future Space Exploration





Cogent
The vision: Space exploration

WSNs –reality

Market forecast:

2014- $50bil. , $7bil in 2010 (2004)

2014- $5-7 bil. sales (conservative)

2011-$1.6 bil. smart metering/ demand response

Infineon tyre sensor

Connecting 466 foil strain gages to a wing box

Industrial Markets- **old and new; mostly wired replacements; generally continuous monitoring systems with "data-made-easy" features and internet connected**

Prompted by regulations and drive towards process efficiency or else…

the "cement motes" from Xsilogy come with 30 min warranty!

Invensys asked a Nabisco executive what was the most important thing he wanted to know. The reply came without a moment's delay: "I'd like to know the moisture content at the centre of the cookie when it reaches the middle of the oven."

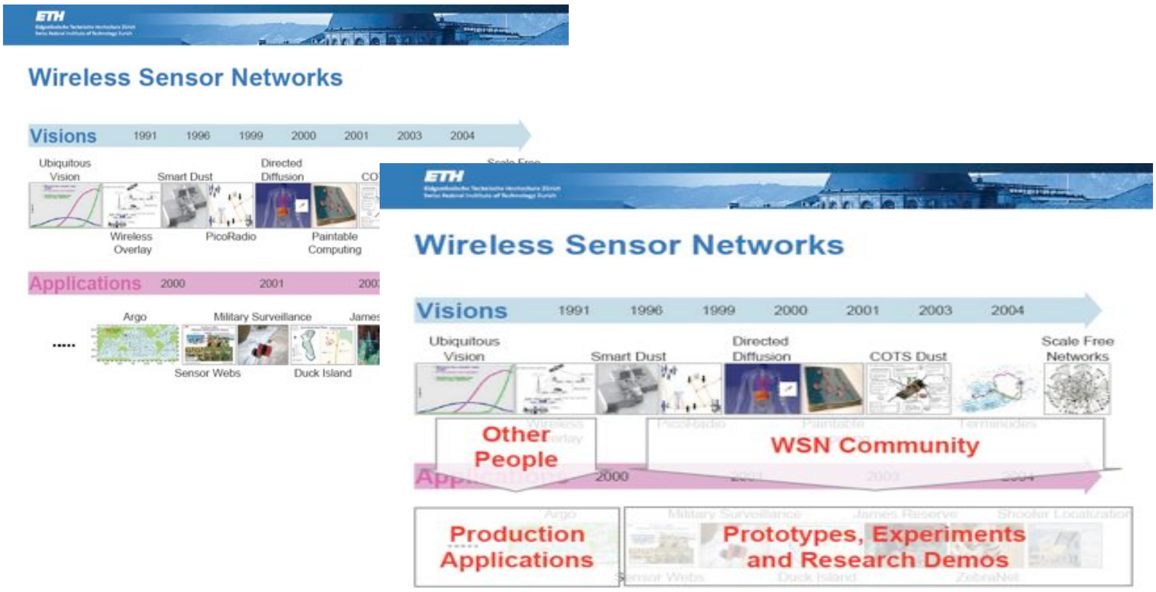
Research: **mainly newly enabled applications; "macroscopes"; adventurous money savings ideas**

Mars video

- mars.wmv

Forming of the WSN Community

(slides from Deployments, Test and Validation of Sensor Networks, Jan Beutel, ETH, 2006)



The basic needs- platforms

(slides from Deployments, Test and Validation of Sensor Networks, Jan Beutel, ETH, 2006)

-large number of

-test beds….application specific

-tendency towards **"the big mote"** concept

…to enable

- Large(er) scale WSN designs
- Support for WSN infrastructure
- Specialist data centric/information centric/service based architectures
- Distributed architectures (vs centralized ones)
- In-network processing
- Care for the un-expert user

…all to fit into

…the WSN design space (Ray Komer, ETH, 2004)

deployment
mobility
cost, size, resources and energy
heterogeneity
communications modality
infrastructure
network topology
coverage
connectivity
network size
lifetime
other QoS requirements

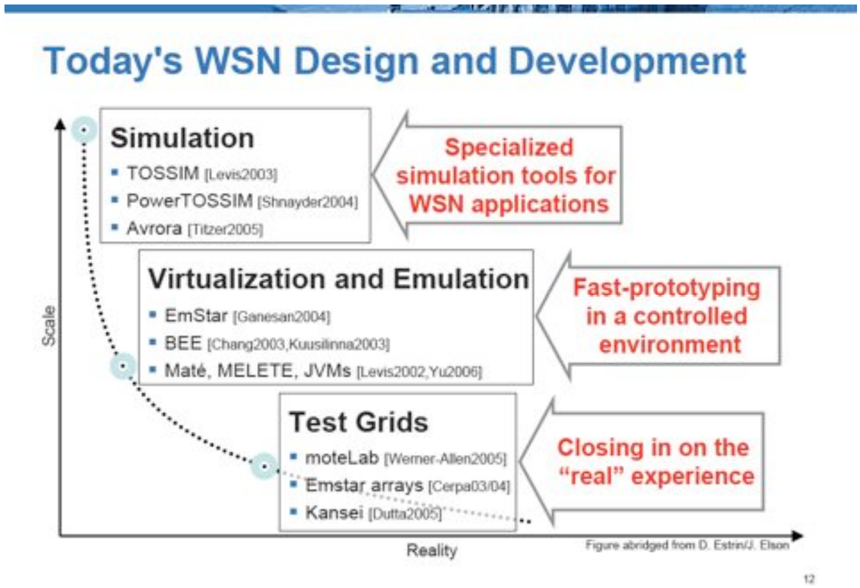
Highly theoretical works

Vs

practical deployments

…and developed through…

(slide from Deployments, Test and Validation of Sensor Networks, Jan Beutel, ETH, 2006)



WSNs - pushing the frontiers

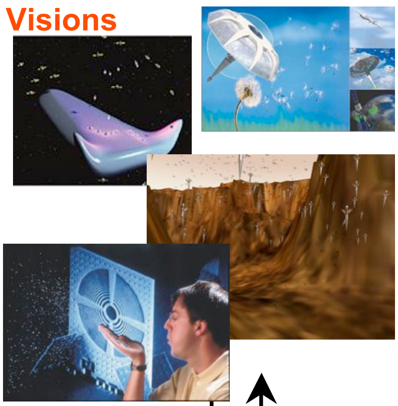
The motivational square

Practical, application oriented research and deployments

…forget about throwing them from the back of that plane!…

Making the most out of a bad situation

Visions



Commercial endeavours

Internet able Microclimate, soil moisture, disease monitoring

Research space

Research/Adoption roadblocks

Industrial needs

Largest part of community

Theoretical research for large scale networks

WSNs – the motivational square

Practical, application oriented research and deployments

Visions

Research space

Research/Adoption roadblocks

Industrial needs

...enable throwing them from the back of that plane!...

Largest part of community
Theoretical research for large scale networks

Part 2
Current "out of the lab" WSN deployments – successes and failures

Real life deployments- state of the art

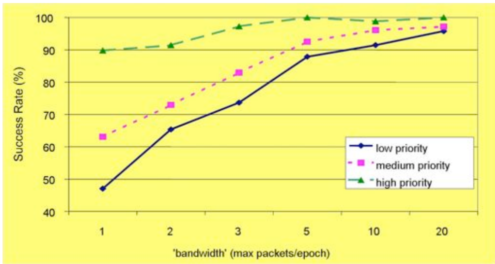
…forget about throwing them from the back of that plane!...

Real life

- **deployments- Floodnet, Glacsweb and SECOAS projects**

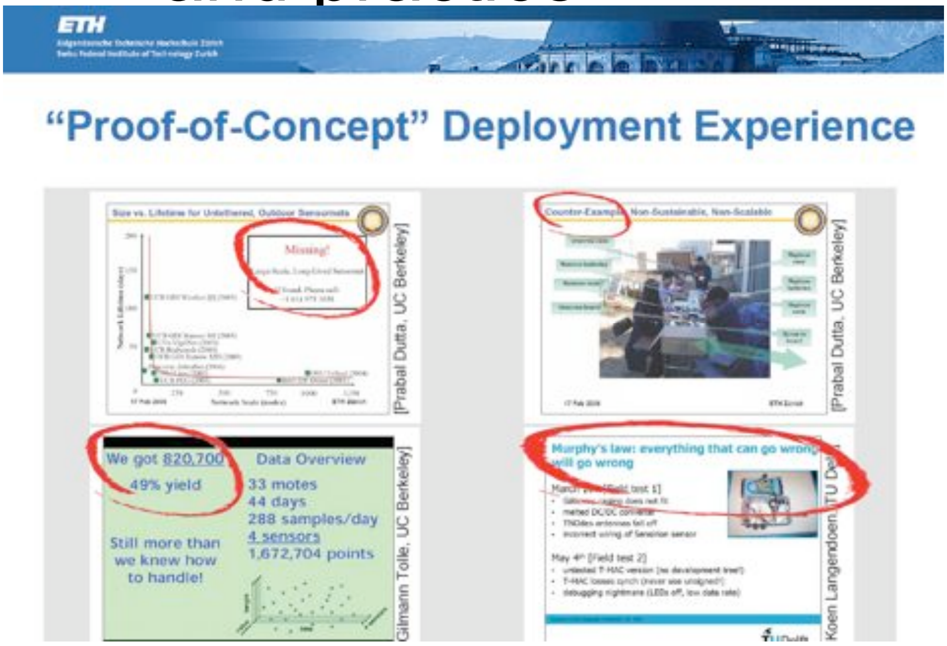
SECOAS

- Adapt sampling rates & Adaptively log data
- Transmit selected data to radio buoy
- Autonomous adaptive control is needed in environmental sensor networks
- Network protocols must support and respond to application semantics (be app aware)
- In simulation adaptation was almost as good as optimal sliding window
- In practice it dealt well with change from calm to stormy
- QoS?



Lessons from Floodnet, life under your feet and other works

Matching the theory and practice



WSN - Ready to get out of the lab ?

Past and current deployments – NO

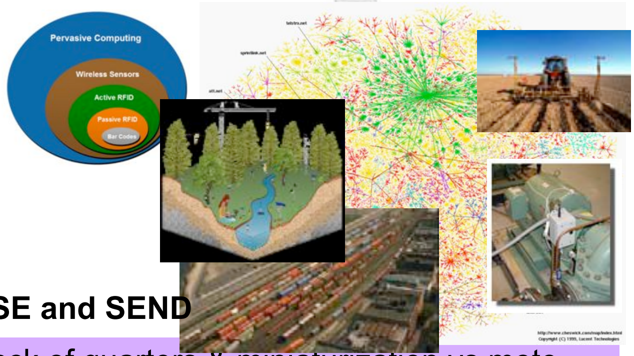
- **Mostly pilot studies**
- **Very low yield**
- **“Hacked” designs**
- **Too tailored**
- **Small nets**

Either or:
-Device (miniaturization)
-System (networking)

No opportunity to apply deployment lessons to the same problem/application

WSN – theoretical wonders

- Scoping of large scale applications
- Complex problems solved for individual functional components/services
- Theoretical proofs and simulation only
- Lack of integrative work



Visions led	SENSE and SEND
1. Dust size- mm cube	1. Stack of quarters & miniaturization vs mote life trade-off
2. Unplanned deployment	2. Planned, carefully measured; ID based
3. Distributed	3. Gateway based – centrally controlled; backboned
4. Millions of	4. Hundreds at most (ExScal)
5. Re-configurable nets	5. Hard coded
6. Self-healing	6. Prone to failure (more than 50% usually)
7. Scalable	7. Only through complete re-design
8. Autonomous	8. Tightly controlled
9. Information systems	9. Data acquisition – relay to base
10.Collaborative decisions	10. Central post processing

Part 3
Research challenges for large scale sensing and actuation

WSNs – back to the motivational square

COGENT computing

Practical, application oriented research and deployments

Visions

Research space

Research/Adoption roadblocks

Industrial needs

…enable throwing them from the back of that plane!…

Largest part of community

Theoretical research for large scale networks

The Grand WSN challenge

COGENT computing

Facilitating the migration of pervasive sensing from future potential to present success

VLS networks as

Scientific instruments
Permanent monitoring fixtures

"The network is the sensor" →

Design space

- Care for the un-expert user – "beyond data collection systems"
- Robustness, fault tolerance
- Long life – across system layers and system components- in network processing &distribution
- Maintenance free systems – scalability, remote programming &generic components/ infrastructure

Design Issues

The problems:
-point measurements reporting often outside the scope of deployment

-time-space link implied as crucial

-user needs global and/or change/event driven information as deployment outcome

Design for re-use

Don't re-invent the wheel

Design "big" to successfully go "small""

Hang on to the deployment expertise

Possible solutions:
-In-network information interpretation

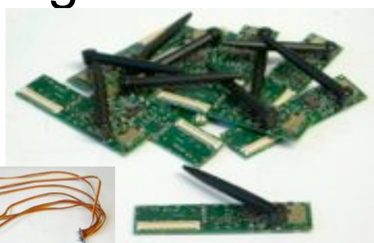
-Robustness of information - cross-layer design & top down, integration, distribution

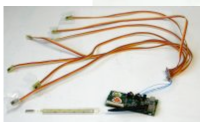
-Optimized query-able systems

Achieving the goals- system components

Platforms & tools- towards the "big" mote?

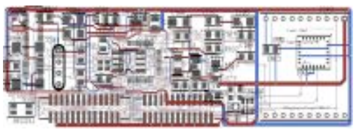
Cogent uses- the Gumstix –FFMC





•400MHz xScale processor,
•16Mb Ram & 64Mb persistent storage

•on-board Bluetooth; + ZigBee + WiFi
•add-on boards expanding capability
•allows custom built sensing modules



•full Linux kernel - ease of use/debug
•generic- wide range of applications

Tools
-SenSOR – in house algorithmic simulator
-HW/SW co-simulator/ rapid deployment tool
-NS2

Software - design features

- designing for information visualization - Field sensing – Mapping
- designing for robustness and long life - Fault Detection and management
- designing for information extraction- Complex Querying
- designing for practical applications –case study here Body Sensing Networks
- designing for robust services support

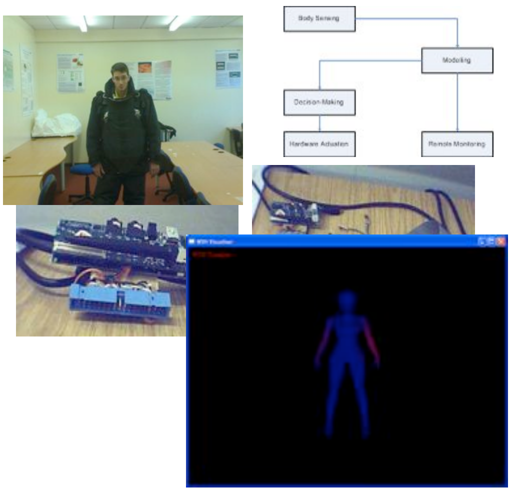
Designing for practical applications

BAN

EPSRC & Industry

The problems:
- Robustness of deployment
- Technologies Integration
- Fitness for purpose
- Non-experts will use it!!!

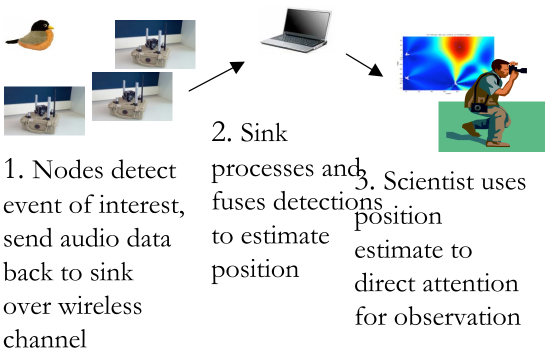
End-to-end system design approach



Bioacoustic monitoring

Deborah Estrin (UCLA, CENS)

Lewis Girod (MIT, CSAIL),



Designing for information extraction

The problem:

- very large data sets from very small networks

(8 hours continuous recording @ 48KHz = 10GB/Node)

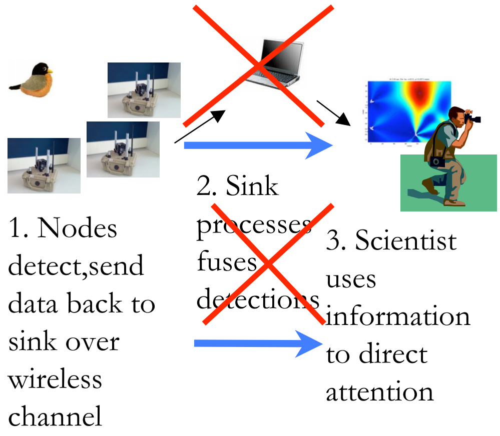
- retrieval of data undesirable and inefficient (bandwidth/energy constraints)

Possible solution: Data reduction to information IN NETWORK

- Information abstraction- essential to any practical usage of large intelligent sensor networks
- enables the user to formulate complex queries ("qualitative" synergy between semantic groupings of points)
- Incorporate space and time

Complex Query Processing Approach

Most networks are aimed to be "information" tools



Designing for information visualization

Information mapping

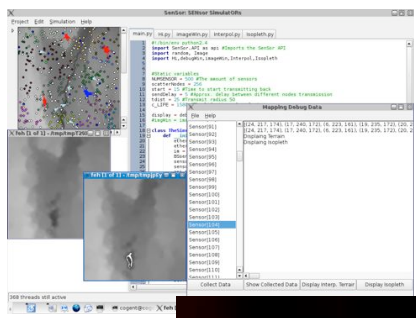
Give the user a global real-time view and a zooming tool!

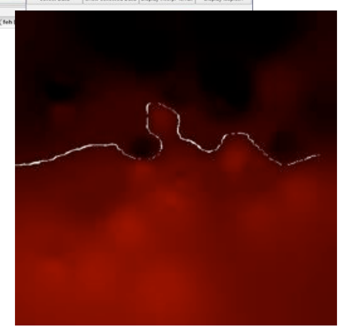
Problems:

- follow on from info extraction
- field sensing lends itself to it
- difficult to bring down the macroscale research due to resources constraints
- app artefacts would be useful- isophlets?

Possible solution

- customize macro to fit at micro scale
- make heavy use of the information extraction strategy and supporting data routing mechanics
- clever interpolation and data fusion
- distributed storage (semantically) of compressed data





Designing for robustness and long life

Problems:

•Harsh environments/ unattended operation

•HW defects – common

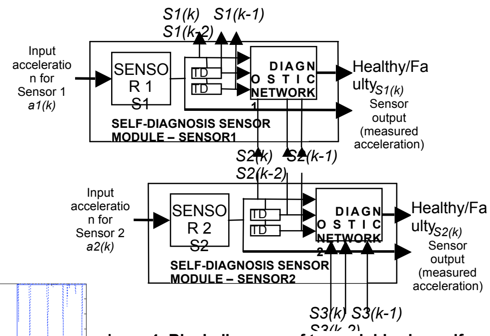
•Wireless comms - unreliable

•Limited power resources

•Dynamic network topology - lost sensing data, connectivity coverage

Fault Detection and management

…network life-time, reliability and "quality of service" part of the design spec…



igure 4: Block diagrams of two neighboring self-diagnosis sensors (*a1(k) = a2(k)*, in this study)

The solution: WSN fault management framework

- ensure sensing coverage
- ensure connectivity coverage
- ensure QoS
- longer network lifetime, fidelity/throughput of data, timeliness of responses

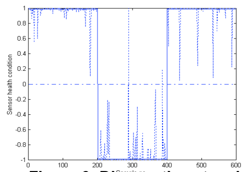


Figure 6: Diagnostic network performance

Designing for robust services support

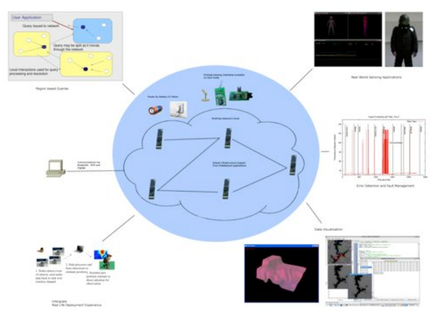
Problems:

- new deployments/application areas - enabled through mapping, querying, localization, fault detection, etc
- low maintenance, industrial strength but light-weight WSNs are likely to be needed to be pretty soon
- usability+ maintainability + deployability- already an issue

Possible solutions

- Have your tools ready
- Develop, deploy, test and re-design
- Distributed SenSor
  - lightweight execution environment for SenSor simulations
  - contains the full functionality of SenSor
  - code transfer development to hardware -a 'one-click' approach to code deployment

Putting it all together- testbed



Part 4
Matching application requirements with available technology – Body sensor network case study

Introductory video

Gaura, Brusey ISIE, Cambridge 30/6/2008

Suit Environment

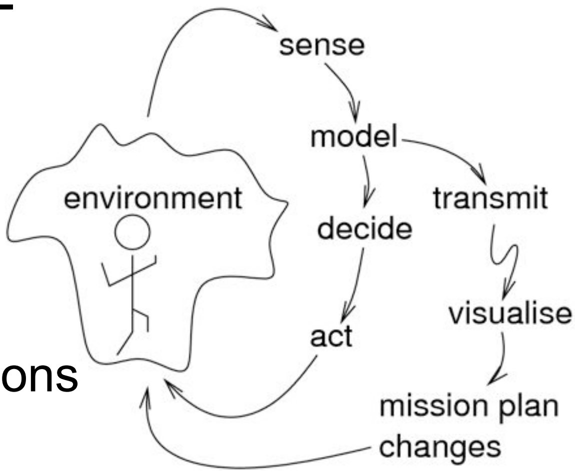
- Increased heat production and reduced ability to remove heat results in storage
- Thermoregulatory system becomes unable to correctly regulate core temperature
- This may result in physical and psychological impairment
- Increased risk of making an avoidable error and jeopardising the mission

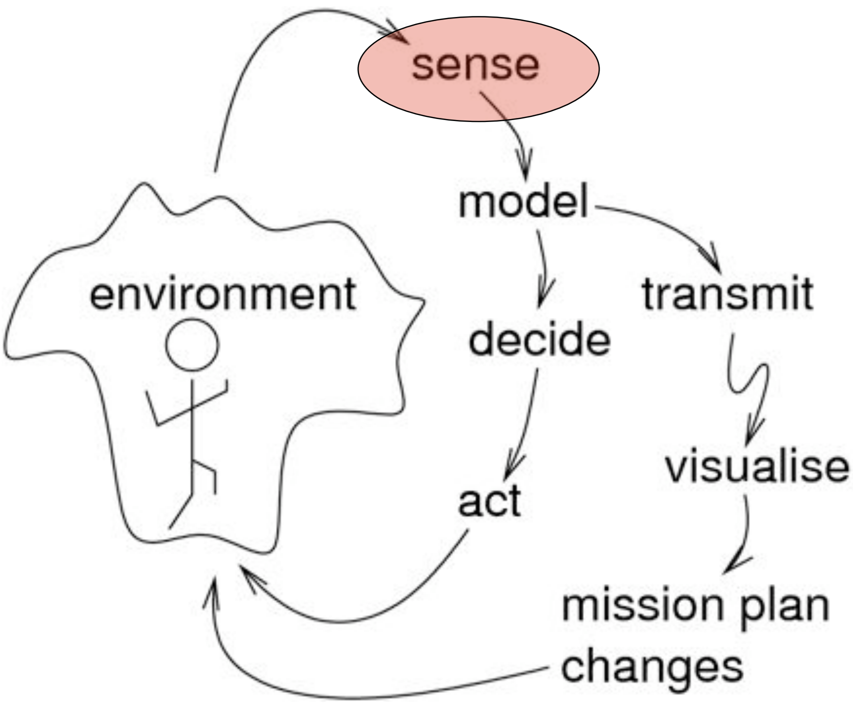
BSN Requirements

- providing detailed physiological measurement, hence providing better insight into what is happening to the human body,
- supporting on-line and real-time extraction of accurate human thermal sensation estimates based on multiple sensor measurements,
- reporting of useful information (rather than data) to a remote station, thus enabling rapid assessment of hazardous situations,
- allowing the provision of thermal remedial measures through control and actuation of systems commonly integrated with armoured suits

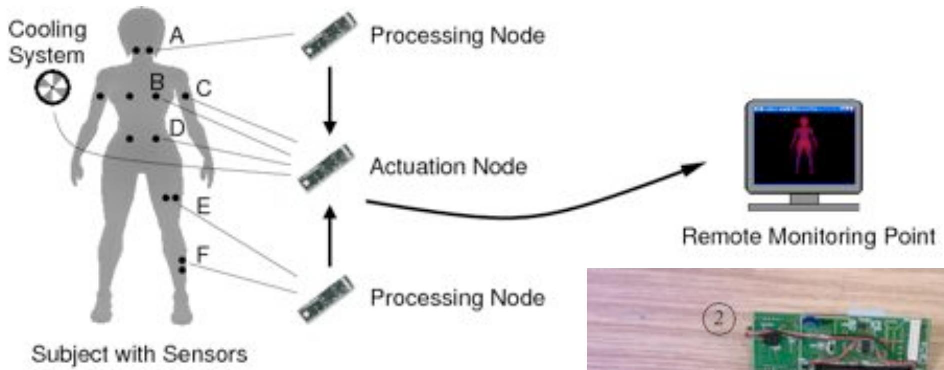
Architecture

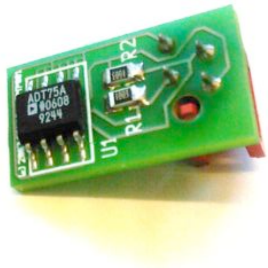
- Sense-model-decide-act architecture
- Two control loops
  - Rapid feedback to autonomously adjust cooling
  - Support for modifications to mission plans and investigation into the construction of the suit.

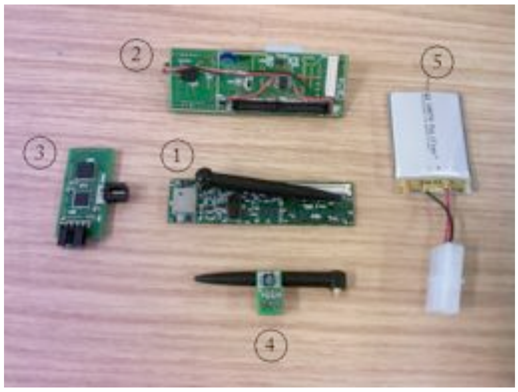




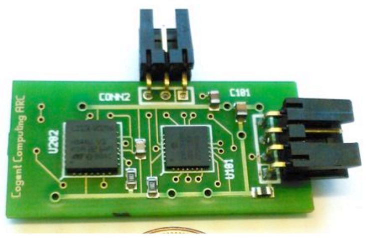
Hardware Components



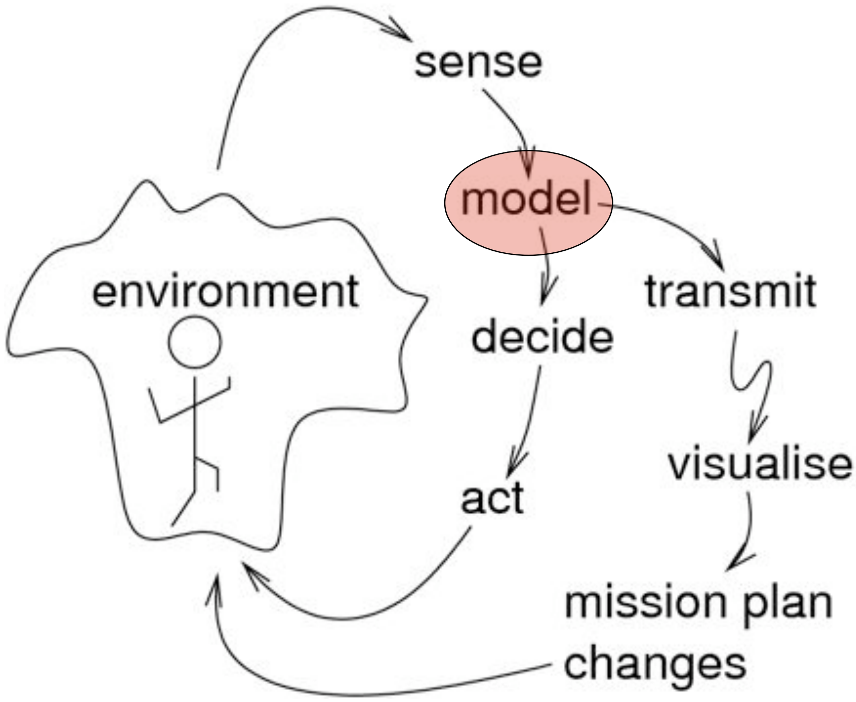




Additional Sensors



- Integrated temperature and acceleration sensors, plus microcontroller
- Allows posture detection and pre-processing of data
- Pulse oximeter for additional health information



Processing

- Basic filtering performed on sensor node
  - Allows rejection of invalid data and generation of alarms
- Additional filtering using a Kalman filter on the processing nodes
  - Smooths data as well as providing estimates of error
- Modelling of thermal comfort performed using a Bayesian Network

Filters and fusion

- Why filter?
  - – Basic measurements may be too noisy
  - – Can't estimate gradient meaningfully otherwise
- Why fuse measurements?
  - – Two measurements are more reliable than one
  - – Allow for / detect faulty sensors

Moving average

- Simple moving average
  - – Average last *N* measurements

$$\hat{x}_t = \frac{1}{N} \sum_{i=t-N}^{t-1} x_i$$

- Exponential moving average
  - – Weight recent measurements more

$$\hat{x}_t = \alpha x_{t-1} + (1 - \alpha)\hat{x}_{t-1}$$

  - – Note: this is a recursive algorithm
  - – α is usually small (say, 0.1)

Kalman filter

- If we have a linear system with some noise:

$$x_t = Ax_{t-1} + Bu_t + \varepsilon_t$$

- Where
  - *x* is the state vector,
  - *A* is a square matrix that defines how the state evolves over time,
  - *B* specifies how the control affects the state, and
  - ε is Gaussian noise with a variance of *Q*
- Note: we'll ignore control in this description as it is rarely relevant to WSN

Kalman filter

- AND, if the measurement is a linear function of the state (plus some noise)

$$z_t = Hx_t + \delta_t$$

- Where
  - δ is Gaussian noise with variance *R*
  - *H* is the sensor model

Kalman filter

- AND, if the initial belief state is known with a covariance P_0
- Note: large P_0 allows for roughly known initial state
- Then a Kalman filter provides an optimal estimate

Kalman filter

- Predict step:

$$\hat{x}^- \leftarrow A\hat{x}$$
$$P^- \leftarrow APA^T + Q$$

- Estimate step:

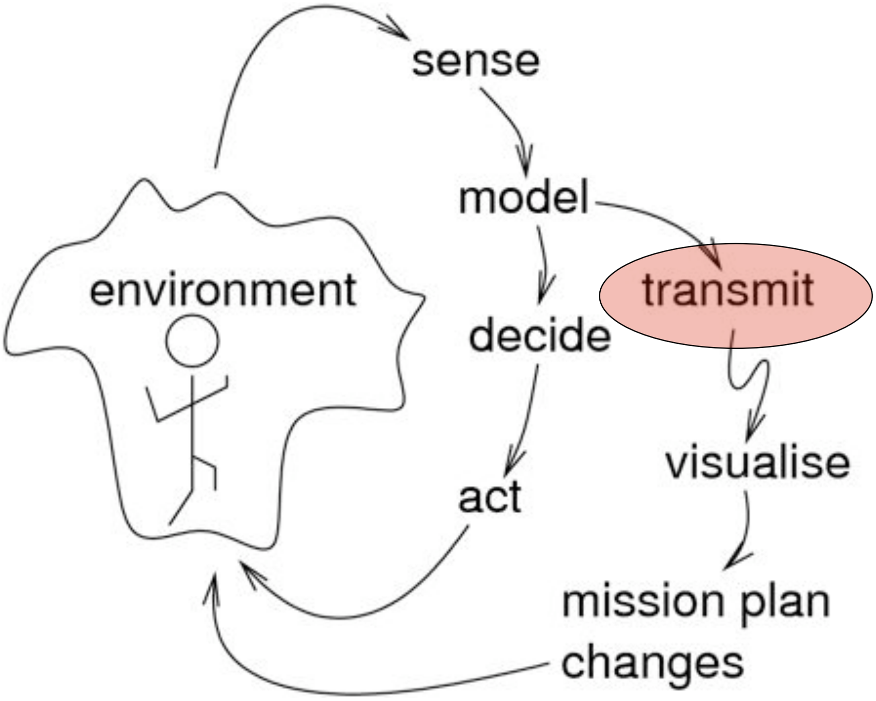
$$S \leftarrow HP^-H^T + R$$
$$K \leftarrow P^-H^TS^{-1}$$
$$\hat{x} \leftarrow \hat{x}^- + K(z - H\hat{x}^-)$$
$$P \leftarrow (I - KH)P^-)$$

Kalman filter

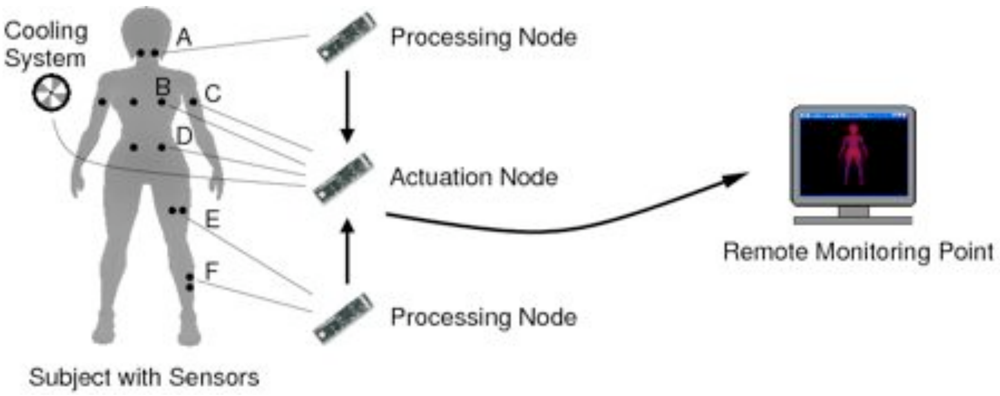
- Multi sensor fusion can be supported via sensor model *H*
- Larger model covariance *Q* indicates less trust in the model (or hidden factors)
- Larger sensor covariance *R* indicates less trust in sensor
- A matrix inversion is needed to calculate Kalman gain *K*
- Basic recursive filter can be implemented in about 10 lines of Python using *numpy* matrix libraries

Comfort Modelling

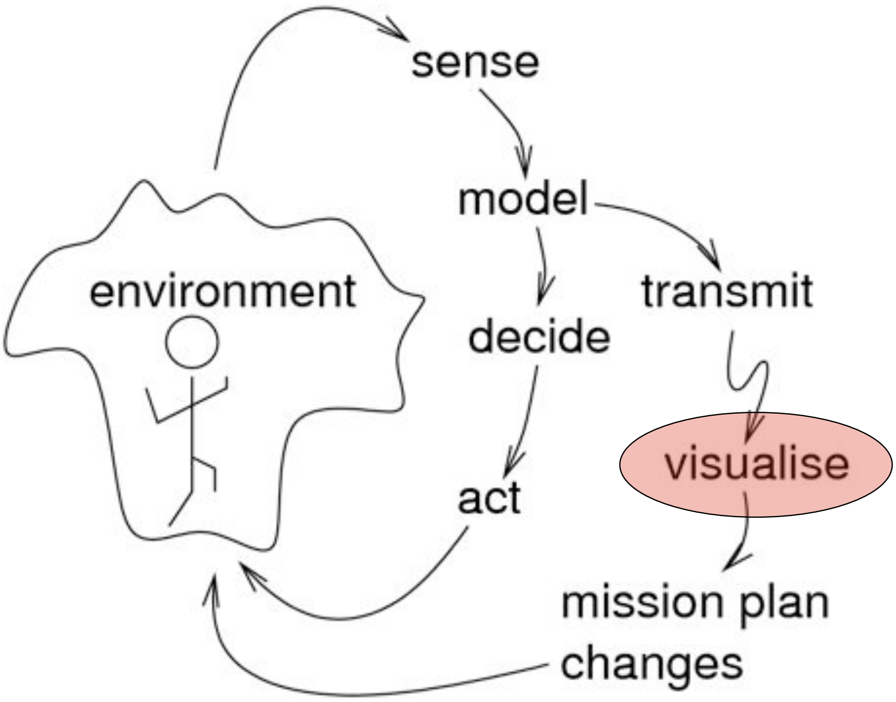
- Takes skin temperature (and optionally core temperature) readings as input
- Provides an estimation of thermal sensation, both per body segment and globally, as output
- The main part of the model is a logistic function based on two main parameters:
  - the difference between the local skin temperature and its "set" point (the point at which the local sensation is neutral)
  - the difference between the overall skin temperature and the overall set point
- Thermal sensation is given in the range −4 to 4, with −4 being very cold and 4 being very hot



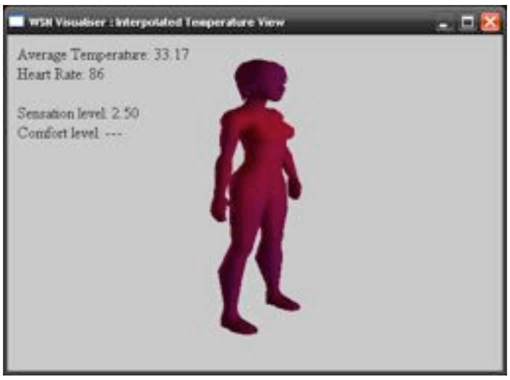
Networking

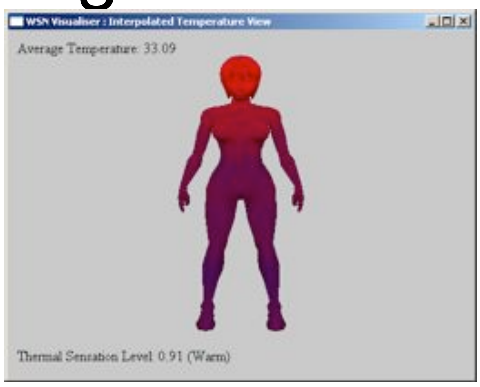


- Wireless links between actuation / processing nodes
- Wireless link between actuation node and remote monitoring point
- Data buffered in case of link failure - may be uploaded at future point

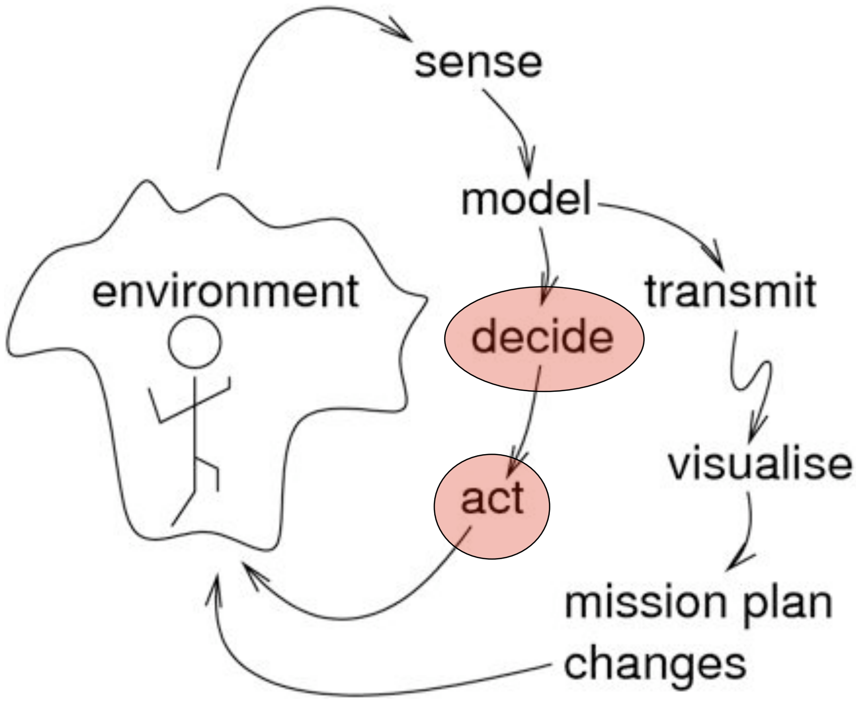


Remote Monitoring





- Main information display panel includes:
  - a 3D figure showing the interpolated temperature distribution across the subject's skin
  - the current average skin temperature, and
  - the current thermal sensation level
- Other panels show the location and status of the sensors and the history of the incoming data



Actuation

- Reinforcement Learning algorithms (such as SARSA) can be used to develop a “policy” for controlling the cooling fan based on the “state” of the user
- Action is to turn fan on or off
- Utility is based on maintaining good comfort levels over time
- Takes account of battery depletion, likely mission duration, posture, as well as current thermal comfort

Part 5
Concluding remarks

Review of tutorial and summary (I)

- (WSNs) offer immense potential for detailed multi-parameter measurements in a variety of applications.
- When coupled with actuation, WSN technology becomes more powerful.
- WSNs have been a buoyant area of study for over a decade.

- Two research strands are apparent with a large gap lying between :
  - theoretical and large scale application feasibility studies - involve highly sophisticated approaches to gathering data from distributed nodes
  - small scale, practical deployments- much simpler, point-to-point approaches that minimize complexity.

- Many proposed designs are complex and sophisticated;
- When implemented/deployed, they have to be considerably stripped down as:
  - particular application requirements impose constraints unable to be met by the theoretically driven overweight designs;
  - much of the technology and techniques taken as given in theoretical designs are neither sufficiently mature nor sufficiently well characterized to be applied in viable, real world deployments.
- Such approach to practical deployment is both expensive and lengthy.

Review of tutorial and summary (II)

- Application led designs
  - rarely need the amount of complexity available at a theoretical level.
  - concerns are for robustness, data integrity, ease of use, long-life, reliability, and maintainability take over as primary design concerns.
- Practical deployment design processes can be sped up by starting with simpler, more focused systems.
- Specificity of application should naturally lead the design process in terms of selecting what off-the-shelf hardware and software can be used, and what bespoke components need to be developed to satisfy the application as a whole.

Review of tutorial and summary (III)

- The tutorial supported the exposition of design techniques and design choices by focusing on an example from within the area of Embedded Body Sensor Networks.
- The embedded body sensor network is neither large nor widely distributed but there are a number of fundamental requirements (the size of the nodes, wearability of the instrumentation, robustness, reliability and fault-tolerance, etc) that dictate the majority of the design and implementation choices.
- WSN technology has not yet reached wide scale adoption.
- Pursuing application driven design processes will enable the development of industrially strong WSN systems which will increase confidence in the technology and contribute to its adoption in near future.

The wisdom of “those who know”

"This technology is going to be revolutionary and will (have) a huge impact on people's daily lives." --Rob Conant, Dust Networks

…but…

- **"Trying to sell a total solution was a mistake. It was too far out there in terms of what people wanted to do."** --Former **Graviton** exec Michael Nova, on how the company bit off more than it could chew.

(extract from Building a wireless nervous system, CNET News.com, May, 2004)