Title
Integration and Use of Embedded Sensor Networks

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Future Science Forum

Integration and Use of Embedded Sensor Networks

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University of California

Digital Habitat Sensing

Center for Embedded Network Sensing (CENS)
Habitat Sensing Group

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Enabled by the National Science Foundation, Science and Technology Center Program, a $47.5 million, 10 year project initiated in 2002

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The Buckley School: *K. Griffis*
New Roads School: *J.A. Wise*

JPL

Center for Integrated Space Microsystems: *L. Alkalai, Manager*

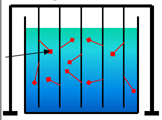
The Digital Sensing Potential


Monitoring and Controlling Natural Processes

- Integrated micro-sensors, low-power processors, wireless interfaces at very small scale
- Monitor "up close"
- Enables spatially and temporally dense, continuous monitoring


Monitoring and Controlling Agricultural Processes

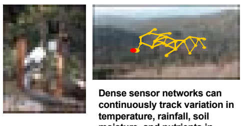
Microorganism Detection



Embedded Networked Sensing will reveal previously unobservable phenomena

Biological Conservation

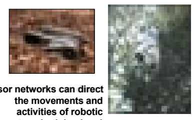
Exploring the benefits of sensor networks: our first experimental test bed



Dense sensor networks can continuously track variation in temperature, rainfall, soil moisture, and nutrients in farms and watersheds

Soil sensors can monitor microbial respiration, nutrients, moisture, fungi and soil organisms

Sensors can monitor without disturbance plants and animals, and their immediate surroundings



Sensor networks can direct the movements and activities of robotic equipment, on both land and in the lagoon

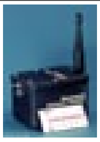
How is it done?

1. **New sensors** in and above soil/water measure nutrients, pollutants, organisms
2. **Wireless data** communication among sensors
3. **Improved engineering** new devices are cheap, durable, easily mass produced
4. **Low power** using battery or solar
5. **Powerful microprocessors** detect patterns in data streams, and combine computing power for running sophisticated algorithms

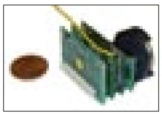
Sensor Node Developments

LWIM III
UCLA, 1996
Geophone, RFM radio, PIC, star network

AWAIRS I
UCLA/RSC 1998
Geophone, DS/SS Radio, strongARM, Multi-hop networks



Sensor Mote
UCB, 2000
RFM radio, PIC



Medusa, MK-2
UCLA NESL
2002

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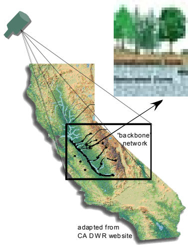
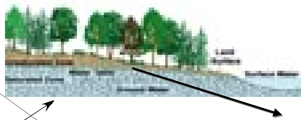
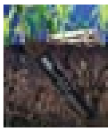
Applications in Watershed management







1. Terrestrial inputs (e.g., fertilizers) impact ground water
2. Inputs and ground disturbances impact rivers, lakes, and ocean (lagoon)
3. Great need for multi-scale monitoring of nutrients and hydrology

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Choosing New Test Sites

1. Small, tractable ecosystem
2. Easy access to many types of habitat, agriculture and microclimates
3. Ability to follow complete watersheds (from mountain to ocean)
4. Essential technological infrastructure (e.g., Broadband Internet access) and scientific expertise (e.g., research stations)
5. Relatively protected natural systems for first deployment from lab to field (e.g., a protected lagoon provides a relatively controlled environment)

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Applications of Digital Sensing

1. Precision agriculture and chemical sensing
2. Monitoring micro-climate
3. Wildlife conservation
4. Robotic sensing (networked info-mechanical systems)

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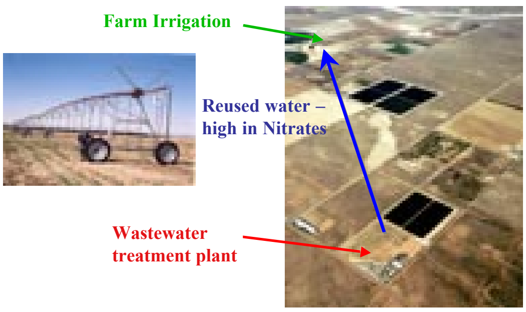
California Agriculture-Environment Test Project



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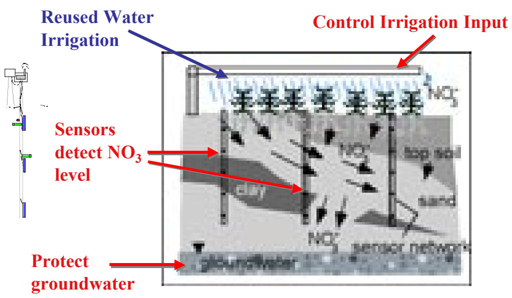
Agricultural Application - California



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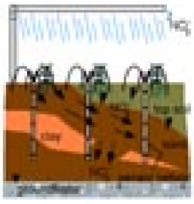
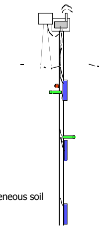
Sensor network calibration





- **Goal:** sensor network error resiliency in heterogeneous soil domain
  - Primarily off-the-shelf sensors
    - soil moisture
    - nitrate ISEs
  - Role of individual sensor noise, failure
  - In situ calibration vs lab calibration
  - Protocols for network calibration

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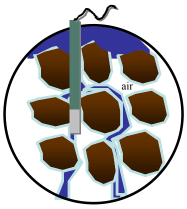
Challenges at the sensor level



- Ion selective membranes need water carry ions
- Resiliency to long-term environmental deployment untested:
  - wetting and drying cycles
  - biofouling
  - material degradation

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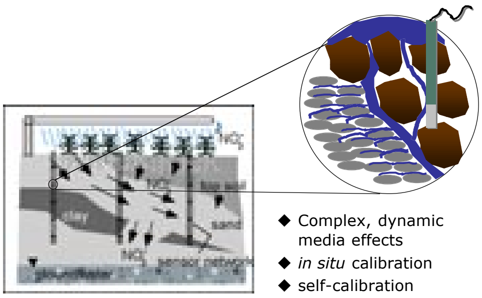
Challenges with *network* calibration



- Complex, dynamic media effects
- *in situ* calibration
- self-calibration

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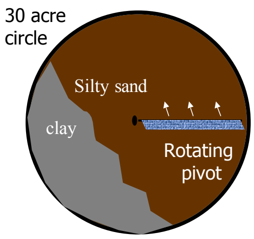
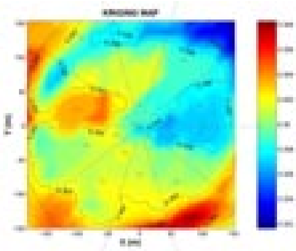
Larger scale spatially distributed flow, transport patterns



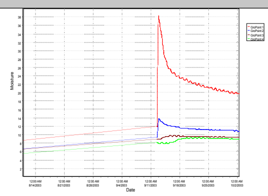
- Too large for us to fully instrument
- Sample randomly throughout
- Employ simulation models to interpolate between sensors
- Geostatistical approaches to parameterize models

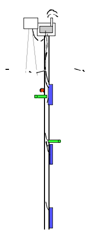
Network Calibration/Error Resiliency/Fault Tolerance



- Too large for us to fully instrument
- Sample randomly throughout
- Employ simulation models to interpolate between sensors
- Geostatistical approaches to parameterize models

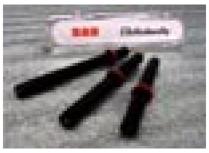
Minimizing cost without cost to research





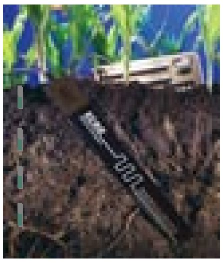
- heterogeneous sensor network
- small numbers of "high end" sensors (e.g. TDR probes)
- large numbers of "low end" sensors (e.g., gypsum blocks)
- collaborative sensing algorithms

New sensor development: nitrate sensors



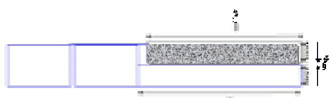
- Current (off the shelf) technology
- Cigar sized
- Relatively expensive
- Not resilient to field conditions
- detection limit typically about 1 ppm

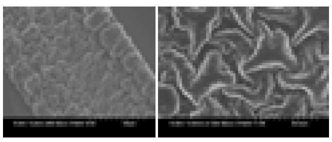
Small scale sensor network: beneath a single plant

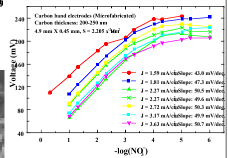


- Many of the same problems apply:
  - lab calibration vs in situ
  - self-calibration
  - sensor longevity
- Form factor will be an issue
  - "mini" Echo?
  - "micro" Echo?

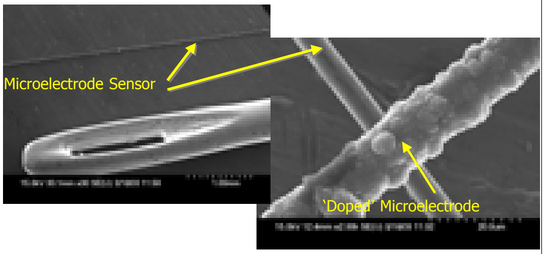
New sensor development: nitrate sensors
Scaling down to facilitate production







Nitrate micro-electrodes



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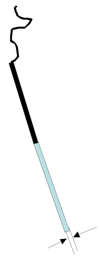
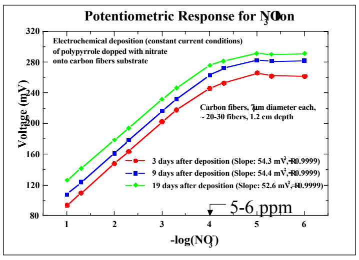
mini-nitrate sensor--single fiber



7 µm carbon fiber



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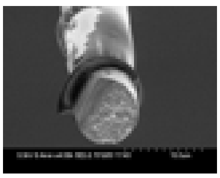
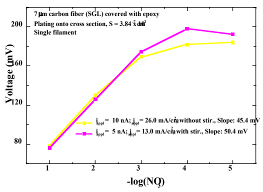
Nitrate micro-electrodes





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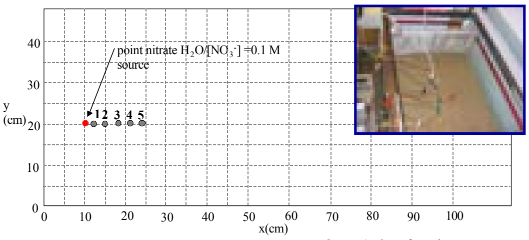
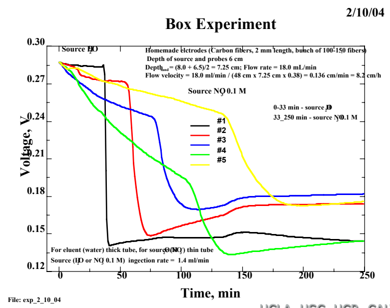
Fiber-based nitrate microsensors "in situ" (saturated sand)

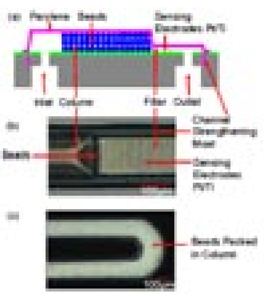


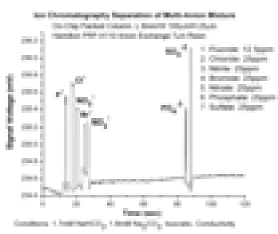
Sensor 1 - 2 cm from the source
Sensors 2 - 5 cm from the source
Sensors 3 - 8 cm from the source
Sensors 4 - 11 cm from the source
Sensors 5 - 14 cm from the source

Fiber-based nitrate microsensors "in situ" (box experiment)



New sensor development: Liquid Chromatography-on-a-Chip Based Ion Sensing -- Fabricated Device





Soil - Root Ecology: monitoring microbial, fungal and root respiration

1. *Online Microscope to monitor root/fungi*
2. *Soil moisture, soil water potential, soil temperature, CO_2 sensing*
3. *Video recording triggered by changes in above ground sensors and imaging criteria*

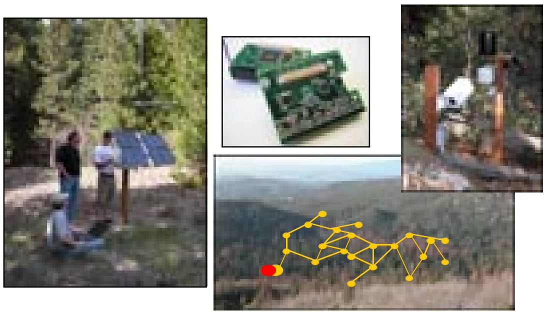
Challenge: robustness of chemical microsensors

1) **pick our battles: where should we invest in sensor development?**
2) **get creative with form factor (take advantage of micro-, and nanofabrication techniques**
3) **calibration/drift/degradation/longevity…how to quantify and standardize?**
4) **…we have only just begun to address REAL environmental conditions (wet-dry cycling, material weathering, biofouling, etc)--a lot of work, but "nonglamorous"**

Applications of Digital Sensing

1. Precision agriculture and chemical sensing
2. Monitoring micro-climate
3. Wildlife conservation
4. Robotic sensing (networked info-mechanical systems)

Habitat Sensing:
Dense Micro-climate Sensor Networks



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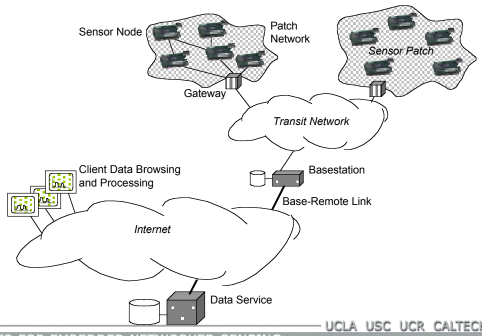
Habitat Sensing:
Dense Micro-climate Sensor Networks



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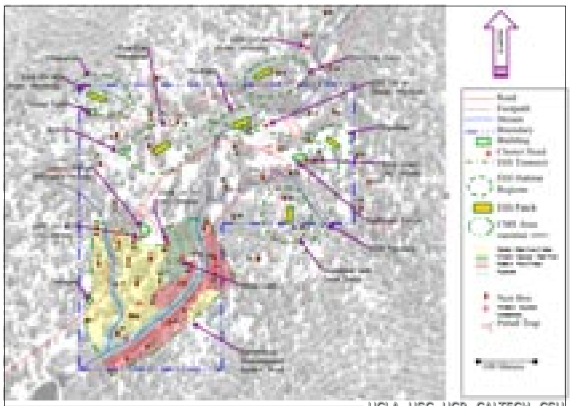

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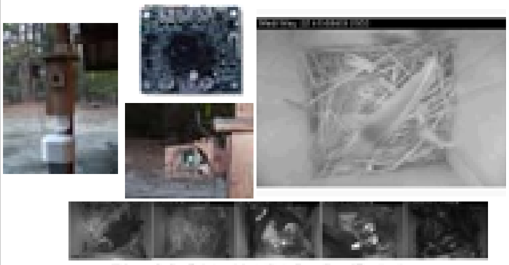
Habitat Sensing Laboratory

Nesting Success and Micro-climate Factors

Biology: *non-invasive direct species observations of reproductive success, behavior, environmental effects, predation*

Technology: *video content analysis, triggered actuation, environmental sensors*



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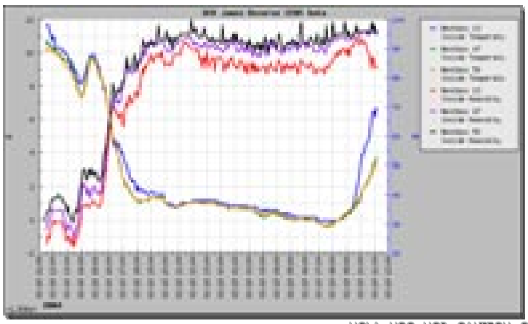
Habitat Sensing Laboratory

Nest Box Microclimate and Proximity Sensors



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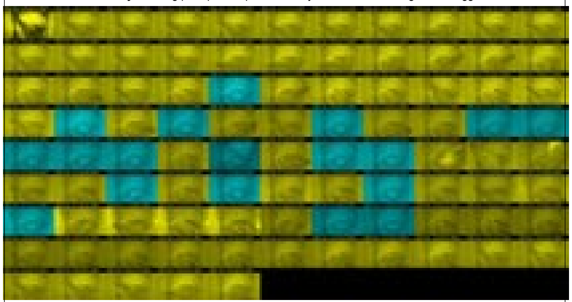
Habitat Sensing Laboratory

Video Content Analysis of Reproduction and Nesting Behavior

Video Content Analysis using principal components analysis: automated recognition of eggs and adult birds



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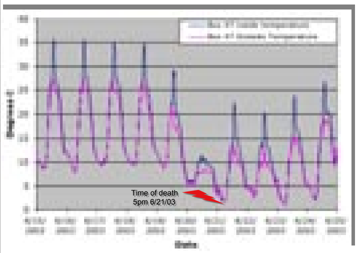
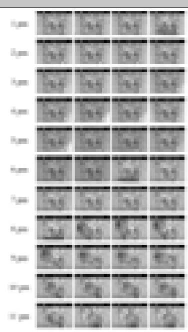
Violet-green Swallow nestling mortality linked to micro-climate variability, June 21, 2003





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Applications of Digital Sensing

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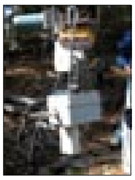
Mobile Sensor Systems:
Terrestrial Applications



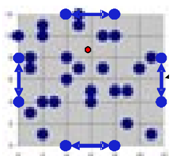
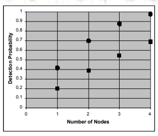



Networked Infomechanical Systems

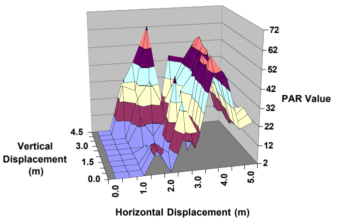
- **Networked mobile nodes**
  - Sensing
  - Sampling
  - Energy logistics
  - Communication
- **Infrastructure Enables:**
  - Deterministic, precise motion
  - Proper node elevation
  - Mass transport at low energy
- **System Ecology**
  - Fixed nodes
  - Mobile nodes
  - Infrastructure

NIMS Progress: Sensing Uncertainty

- Test Hypothesis
  - Constrained articulation will have large impact on sensing uncertainty
- Theoretical and Experimental Investigation
  - Distributed imagers
  - Linear motion
  - Distributed cylindrical obstacles
- Confirm prediction
  - Articulation can have dramatic impact on uncertainty

NIMS Progress: Sampling



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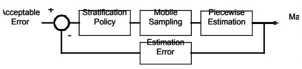
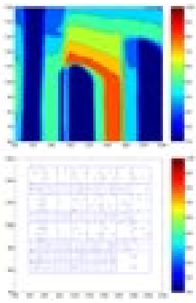
NIMS Progress: Adaptive Sampling and Task Allocation

- Developed
  - Adaptive Sampling Strategy, Architecture, and Algorithms
  - Emstar-based Node
  - Theoretical Analysis
- Autonomous System with Task Allocation in Lab
- Publication at ICRA 2004





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NIMS Physical Systems

- NIMS First Prototype
  - Complete prototype field system end-to-end operation including energy harvesting Sept 03
- Laboratory NIMS operational
  - In use for Adaptive Sampling and Task Allocation
- Sustainable NIMS system
  - Observatory grade sensor suite
  - Deployment at James Reserve in two weeks
- Deployments
  - Wind River Canopy Crane Research Facility
  - James Reserve
    - Microclimate exploratory data

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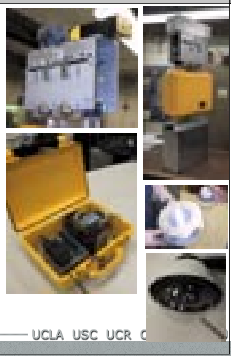
Sustainable NIMS

- Field NIMS Target Capability
  - ***All Observatory Class Sensors***
  - ***All Weather Continuous Operation***
  - ***Microclimate***
  - ***Imaging***
  - ***Planned Spatially-Resolved Carbon Flux***
- Horizontal and Vertical Transport
  - ***High efficiency and high torque, high speed motor***
  - Integral brake
  - Integral odometry
- Vertical Transport
  - ***50m articulation with electromech cable system***
  - Slip ring access
  - AC supply
  - Wireless link to vertical node
- Vertical Node
  - ***Stargate***
  - RH
  - Temperature
  - PAR
  - Acoustic Level
- All Weather
  - Precipitation (sealed and shrouded components)
  - Low Temperature (internal camera system heater capability)
  - High Temperature (precipitation – proof ventilators)
- Power systems
  - Module, individually addressable power
- Designed to
  - ***In Field Upgrade and Modification without Tools***
  - Accommodate robust operation
  - Convenient installation



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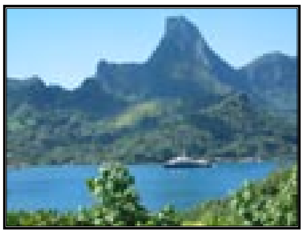
Center for Embedded Networked Sensing

Pioneering new ecological technologies

- Building Partnerships with:
  - Agriculture
  - Aquaculture
  - Public Health
  - Environment
  - Tourism
  - Marine resources
  - Research



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