WTEC Workshop on the U.S. Baseline of Robotics
July 21-22, 2004

Environmental Robotics

Arthur C. Sanderson
Rensselaer Polytechnic Institute

Daniel J. Stilwell
Virginia Polytechnic Institute & State University

Environmental Robotics

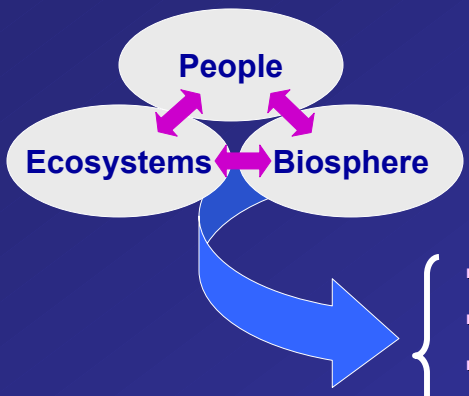
The application of robotics technology, particularly mobile sensor networks, to the observation, monitoring, and remediation of environmental systems.

Challenge: **Monitoring of large-scale distributed dynamic systems with complex interactions and impacts**

Major Subtopics:

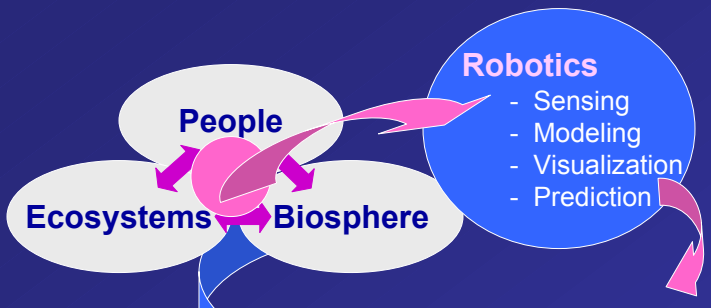
- **Sensors and Sensor Networks for Estimation of Distributed Field Models**
- **Mobility in Complex Outdoor Settings - Multivehicles**
- **Architecture, Control, and Communications - Networks**
- **Algorithms, Planning and Reasoning – Model Estimation**
- **Human-System Interaction – Management and Risk**
- **Implementations for Specific Environmental Domains**

Complex Environmental Systems



- Human Health
- Societal Patterns
- Economic Development
- Security and Defense
- Education

Complex Environmental Systems



- Human Health
- Societal Patterns
- Economic Development
- Security and Defense
- Education

Environmental Systems

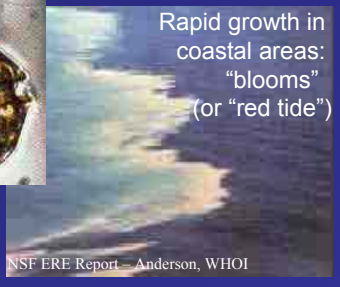
- Example: Algal Blooms in Coastal Areas

Dinoflagellates

Environmental Systems

- Example: Algal Blooms in Coastal Areas

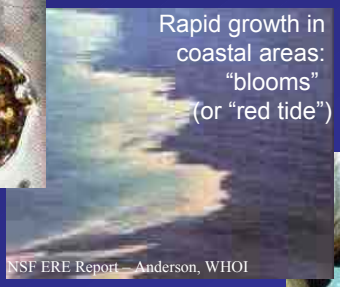
Dinoflagellates



Environmental Systems

- **Example: Algal Blooms in Coastal Areas**

Dinoflagellates

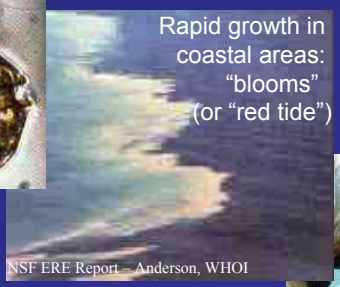


Toxic impact on marine mammals and fish

Environmental Systems

- **Example: Algal Blooms in Coastal Areas**

Dinoflagellates



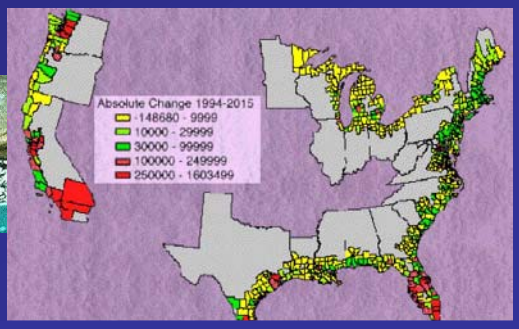
Monitoring
Modeling
Prediction

Toxic impact on marine mammals and fish

Environmental Systems

- **Example: Algal Blooms in Coastal Areas**

Meanwhile:
Coastal Population Trends



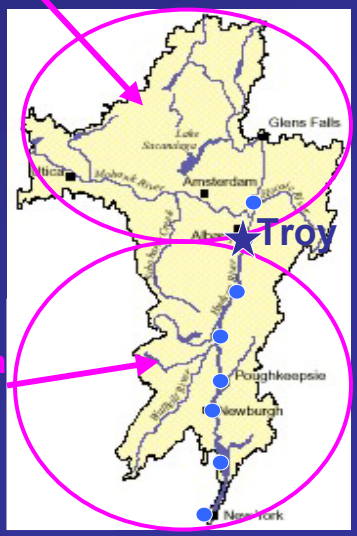
Example: Hudson River and Estuary

Major U.S. river resource
- Economic
- Environmental
- Cultural

Total length: 315 miles
- New York City – Troy (tidal) : 154 miles

Complex and Diverse Ecosystem
- Tidal over 154 miles
- Salt front up to 60 miles
- 200 species of fish

Rich Historical Role
- Transportation
- Economic Resource – Fishing
- Industrial and Agricultural Focus
- Population and Cultural Center



Issues: Critical Environmental Challenges

Expanding Population Trends

- Northward expansion of New York City population
- Expansion of Capital Region
  - Pressures on Land Use
- Industrial Development
- Power Generation
- Water Resources

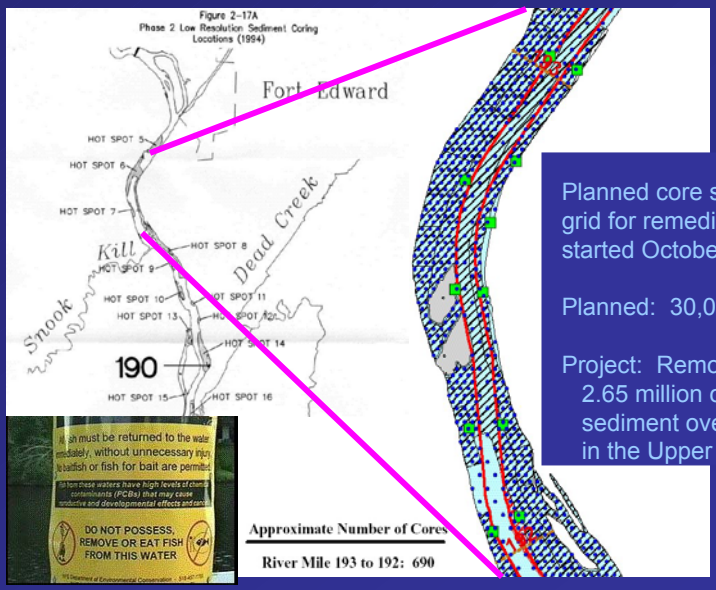
Ecosystem

- Complex biological system
  - Habitats, plant communities,
  - Energy and nutrients
  - Fish and animal populations
- Strong impacts of population, land use, industry

Contaminants

- Sewage, organic wastes, pulp mill discharge
- Industrial oil, paint, metals
- Non-point source pollution – fertilizers, pesticides, acidity
- Specific problems:
  - Heavy metals – cadmium, nickel, cobalt, lead
  - PCB

Hudson River – EPA PCB Remediation Project

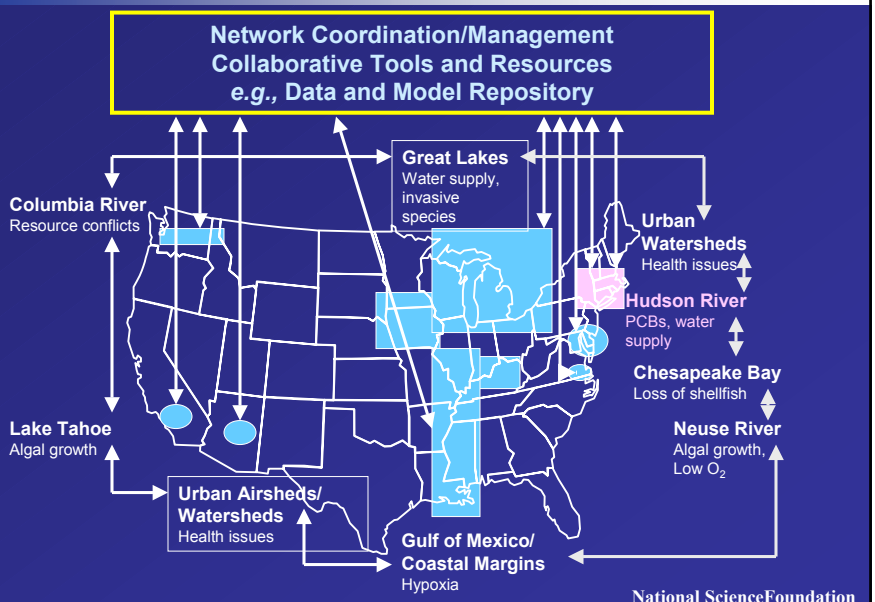


Planned core sampling grid for remediation study, started October, 2002.

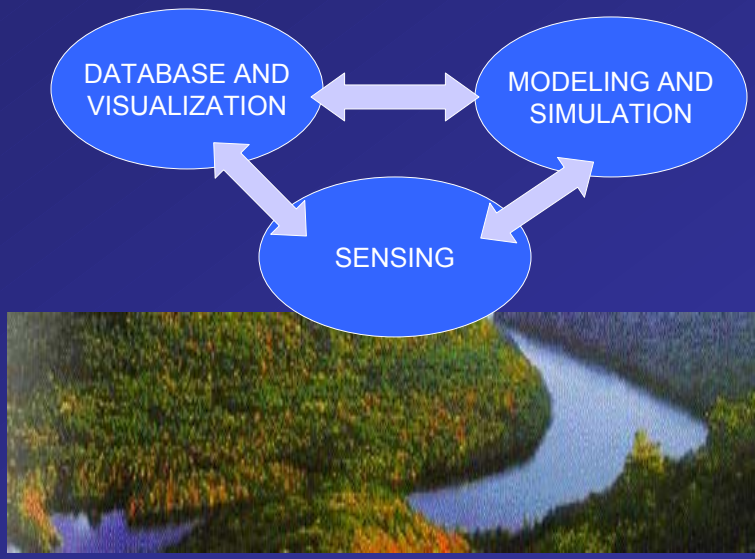
Planned: 30,000 samples

Project: Remove estimated 2.65 million cubic yds of sediment over 40 miles of river in the Upper Hudson

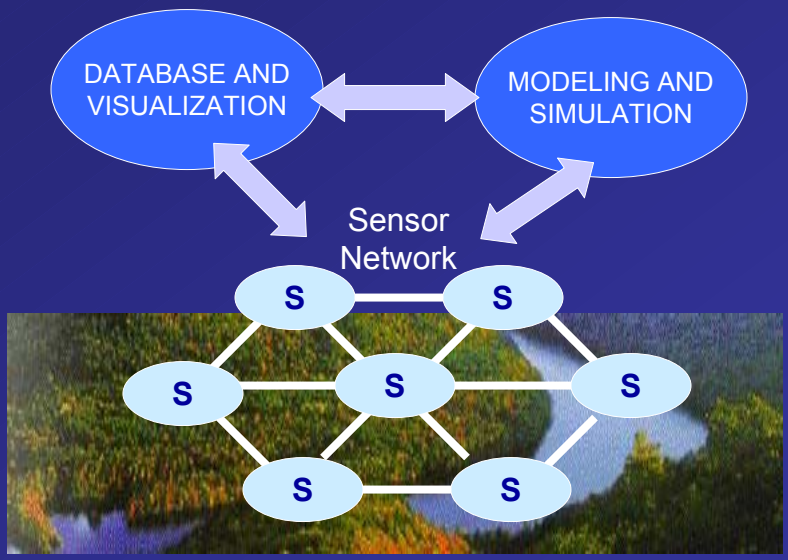
NSF: National View of Environmental Observation Regions



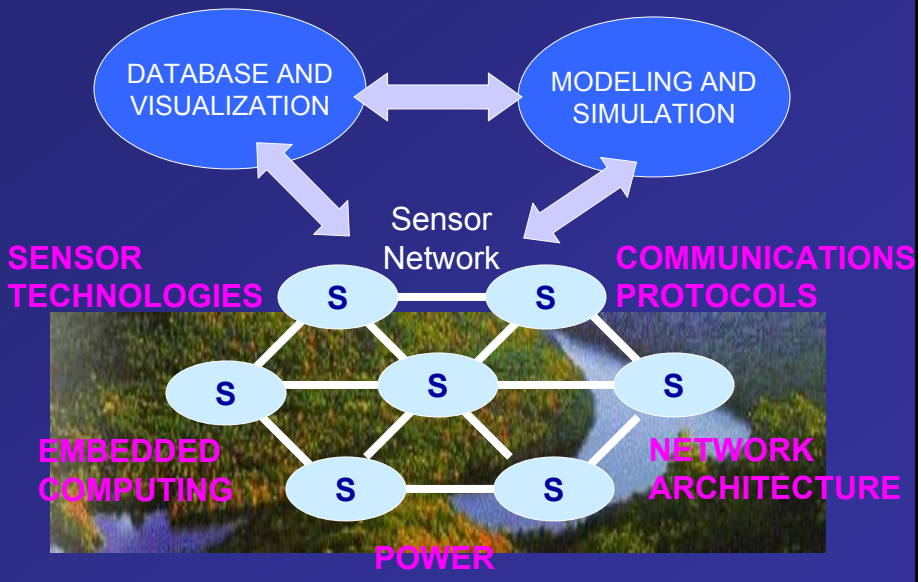
Environmental Research Infrastructure



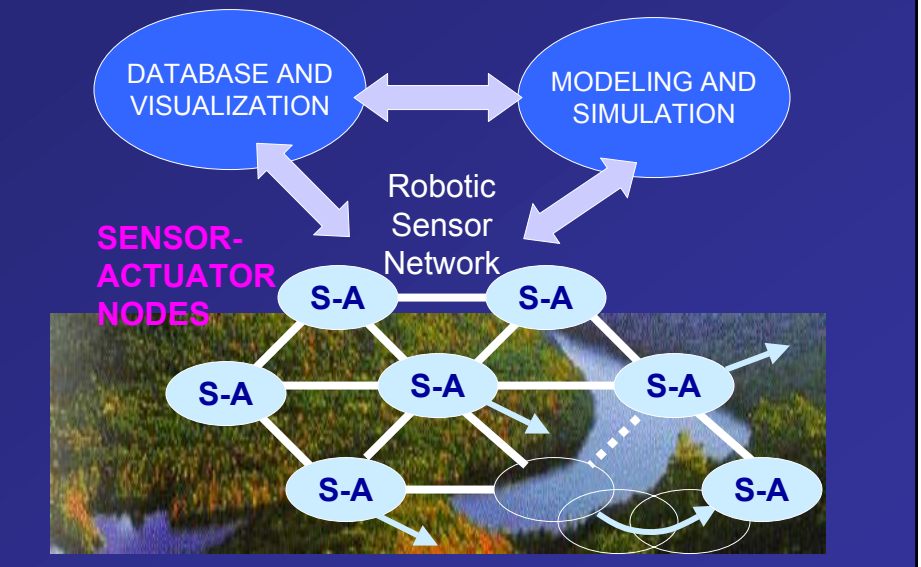
Environmental Research Infrastructure



Environmental Research Infrastructure

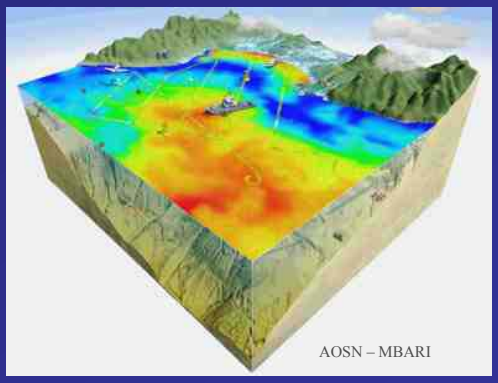


Environmental Research Infrastructure



Major U.S. Laboratories

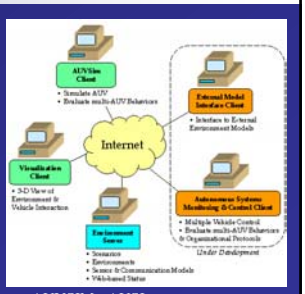
- **MBARI** (Monterrey Bay Aquarium Research Institute)
  - Links: Princeton University – Naomi Leonard
  - Links: MIT
  - Key Investigator: James Bellingham
  - Major Program: AOSN – Autonomous Observation Sensor Networks, AUV Development (Bluefin vehicle)



AOSN – MBARI

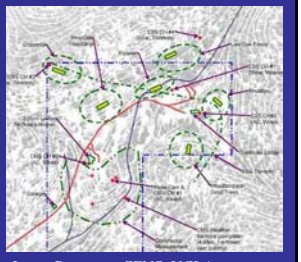
Major U.S. Laboratories

- **RPI** (Rensselaer Polytechnic Institute)
  - Links: Lamont-Doherty Earth Observatory (LDEO, Columbia University)
  - Links: Autonomous Undersea Systems Institute – Dick Blidberg
  - Key Investigator: Arthur Sanderson
  - Major Programs: RiverScope – monitoring rivers and estuaries



AUVSIM - AUSI

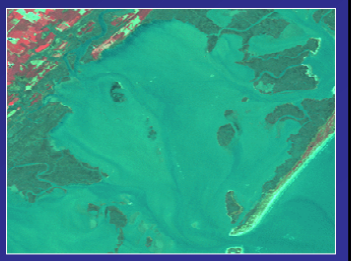
- **UCLA**
  - Key Investigators: Deborah Estrin, William Kaiser
  - Links: USC – Gaurav Sukhatme; UC Merced – Tom Harmon
  - Links: UC Berkeley – distributed network hardware, UCB Motes.
  - Major Programs: NSF STC CENS Center

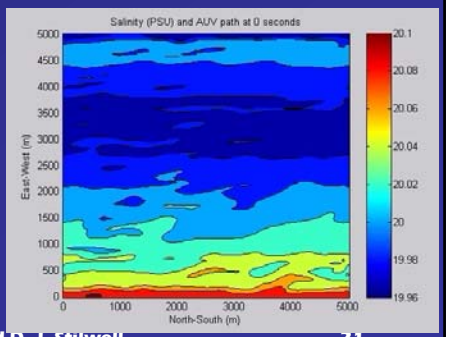


James Reserve – CENS, UCLA

Major U.S. Laboratories

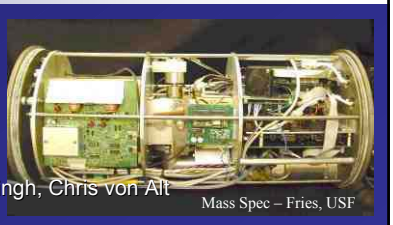
- **Virginia Tech**
  - Key Investigators: Dan Stilwell
  - Links: Virginia Institute of Marine Science; Center for Bioenvironmental Research (Tulane/Xavier)
  - Major Programs: AUV development; multi-vehicle control/estimation





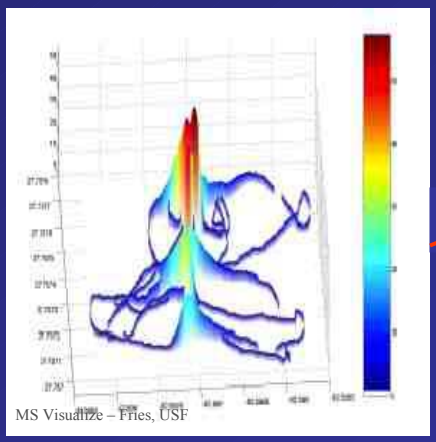
Major U.S. Laboratories

- **USF (University of South Florida)**
  - Key Investigators: Larry Langebrake, David Fries
  - Major Programs: Coastal monitoring; Microsensor development
- **WHOI** (Woods Hole Oceanographic Institute)
  - Key Investigators: Dana Yoerger, Hanumant Singh, Chris von Alt
  - Links: MIT
  - Major Programs: Oceanographic and coast monitoring; AUV development (Remus)

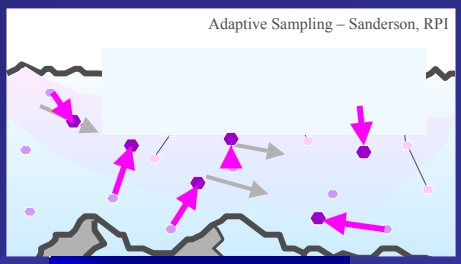

Mass Spec – Fries, USF

- **UC Riverside**
  - Key Investigator: J. Farrell
  - Links: SPAWAR
  - Major Program: Successful plume localization using a REMUS AUV
- **University of Washington**
  - Key Investigator: J. Delaney
  - Links: MBARI, WHOI, NASA JPL, NOAA, Rutgers
  - Major Program: NEPTUNE regional ocean observatory for Northeast Pacific Ocean
- **Other Research Communities:**
  - Oceanography, Hydrology, Environmental Science and Engineering …

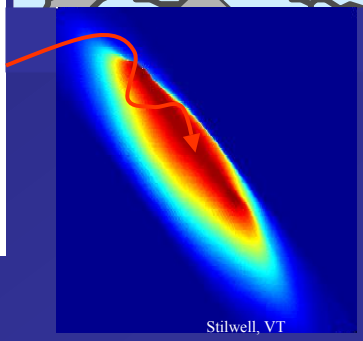
Algorithms, Planning, and Reasoning: Examples



MS Visualize – Fries, USF

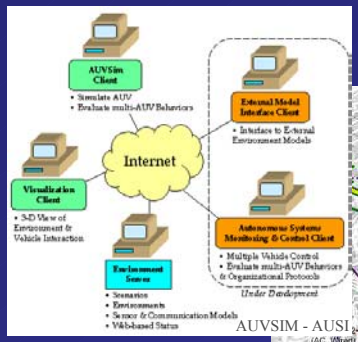


Adaptive Sampling – Sanderson, RPI

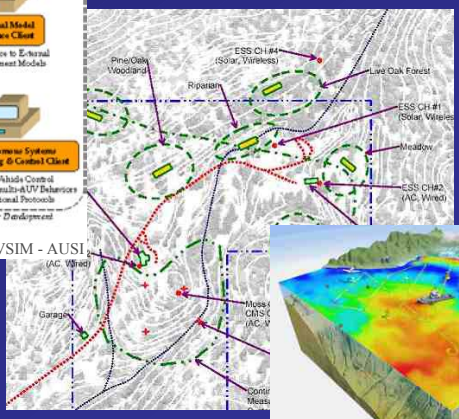


Stilwell, VT

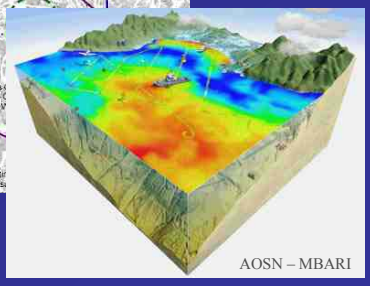
Architecture and Control: Examples



AUVSIM - AUSI



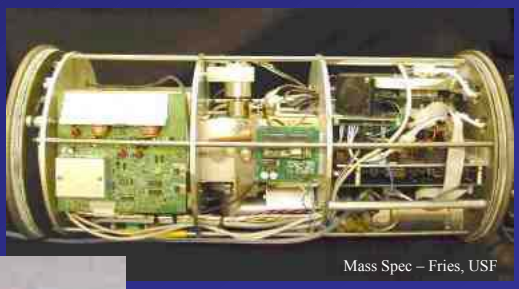
James Reserve – CENS, UCLA

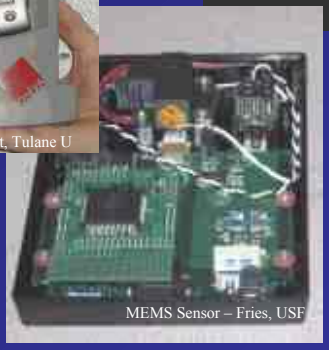


AOSN – MBARI

Sensors and Sensor Networks: Examples

Biosensor – Meffert, Tulane U


Mass Spec – Fries, USF


MEMS Sensor – Fries, USF

ADCP – Wall, USGS

Mobility: Examples


SAUV – AUSI,RPI, Falmouth Scientific


ROV – Fries, USF


Glider – Eriksen, Wash


CENS –UCLA, USC


AUV – Stilwell, Virginia Tech

Accomplishments - Fundamental

- **Environmental Sensor Technologies**
  - Fundamental devices and systems for critical environmental variables, e.g. CTD Sensors, Dissolved Oxygen, Chlorophyll, ADCP
  - Commercial: Wetlabs, Falmouth Scientific, RDI, Crossbow and others.
- **Sensor Networks**
  - D. Estrin, W. Kaiser (UCLA)
  - U.C. Berkeley – Modular sensor network technologies
  - Development of distributed sensor algorithms and applications to environmental monitoring networks
- **Autonomous Navigation**
  - J. Leonard (MIT), L. Whitcomb (JHU)
  - Development and demonstration of underwater navigation algorithms with application to single and multiple autonomous vehicles for environmental observation and monitoring
- **Adaptive Sampling**
  - J. Farrell (UC Riverside), N. Leonard (Princeton), A. Sanderson (RPI)
  - Development of algorithms to guide observation and sampling of distributed field variables in underwater environments

Influential Papers

- J.A. Farrell, S. Pang, W. Li, "Plume mapping via hidden Markov methods," *IEEE Transactions on Systems, Man and Cybernetics, Part B*, vol. 33, no. 6, pp. 850 – 863, 2003.
- J. J. Leonard and H. F. Durrant-Whyte, *Directed Sonar Sensing for Mobile Robot Navigation.* Boston, MA: Kluwer Academic Publishers, 1992.
- E. Fiorelli, P. Bhatta, and N. E. Leonard, "Adaptive sampling using feedback control of an autonomous underwater glider fleet," *Proceedings of the International Unmanned Untethered Submersible Technology Symposium*, Durham, NH, 2003.
- S. I. Roumeliotis and G. A. Bekey, "Distributed multirobot localization," *IEEE Transactions on Robotics and Automation*, vol. 18, no. 5, pp. 781–795, 2002.
- A. C. Sanderson, "A distributed algorithm for cooperative navigation among multiple mobile robots," *Advanced Robotics*, vol. 12, no. 4, pp. 335–349, 1998.
- H. Singh, J. Catipovic, R. Eastwood, L. Freitag, H. Henricksen, F. Hover, D. Yoerger, J. Bellingham, and B. Moran, "An integrated approach to multiple AUV communications, navigation and docking," in *Proceedings of the OCEANS 96 MTS/IEEE Conference*, pp. 59-64, Fort Lauderdale, FL, September 1996.
- Y. Yu, R. Govindan, D. Estrin, "Geographical and Energy Aware Routing: a recursive data dissemination protocol for wireless sensor networks", UCLA CS Department Technical Report, CSD-TR-01-0023, May 2001.

Unsolved Problems

Achieve distributed, energy efficient sensing, control, communications, and localization in large-scale mobile networks, and link to environmental process models.

- **Sensors and Sensor Networks**
  - Real-time, autonomous sensor networks
  - Multisensor fusion
- **Mobility**
  - Single and multivehicle
  - Localization and mapping
  - Energy management
- **Architecture and Control**
  - Autonomous and teleoperation
  - Distributed control and Communications
  - Behavioral and model-based
- **Algorithms, Planning, and Reasoning**
  - Multiscale Spatial-Temporal reasoning
  - Adaptive behavior and adaptive sampling
  - Improved models and model-based reasoning
  - Estimation and uncertainty management
- **Human-System Interaction**
  - Visualization
  - Decision support and risk analysis
  - Educational role

Research Goals for Federal Investments

- **Group Research Programs**
  - Sensor and sensor network development
  - Mobile platform development – multivehicle systems
  - Algorithm and architecture development
- **Cooperative Large-Scale Programs**
  - Environmental Domains and Needs
    - E.g. Rivers and Estuaries, Air, Soil
  - Environmental Field Facilities
    - Focused programs and deployment
  - Engineering Analysis Networks
    - Cooperative cyberinfrastructure
  - Multi-disciplinary coordination – Multiagency coordination
    - E.g, Engineering, environmental science, biology, computer science, oceanography
    - Defense and Security Applications

Accomplishments Outside U.S.

- **Japan**
  - Lake Biwa Research Institute
    - Key Investigator: Prof. Kumagai
    - Area: Mobile robotics for monitoring of lakes
  - University of Tokyo
    - Key Investigator: Prof. Ura
    - Area: Development of AUV's for oceanographic observation
- **Europe**
  - CNRS
    - Key Investigator: Prof. Maria Joao Rendes
    - Area: Signal and information processing; Adaptive sampling
- **South America**
  - EULA (Center for Environmental Sciences, Universidad de Concepcion, Chile)
    - Key Investigator: Dr. Oscar Parra
    - Area: Monitoring and preservation of wilderness water resources

Opportunities for International Cooperation

- **Shared Infrastructure**
  - Sensors
  - Mobile Platforms
- **Methods and Algorithms**
  - Dynamic Monitoring
  - Adaptive Sampling
- **Environmental Domains**
  - Oceans and Coastal Regions
  - Rivers, Estuaries, and Lakes
  - Air
  - Soil