Adaptive Decentralized Control of Underwater Sensor Networks for Modeling Underwater Phenomena

Carrick Detweiler[‡†], Marek Doniec[†], Mingshun Jiang[⋆], Mac Schwager[†], Robert Chen[⋆], Daniela Rus[†]

† Massachusetts Institute of Technology
‡ University of Nebraska-Lincoln
⋆ University of Massachusetts–Boston

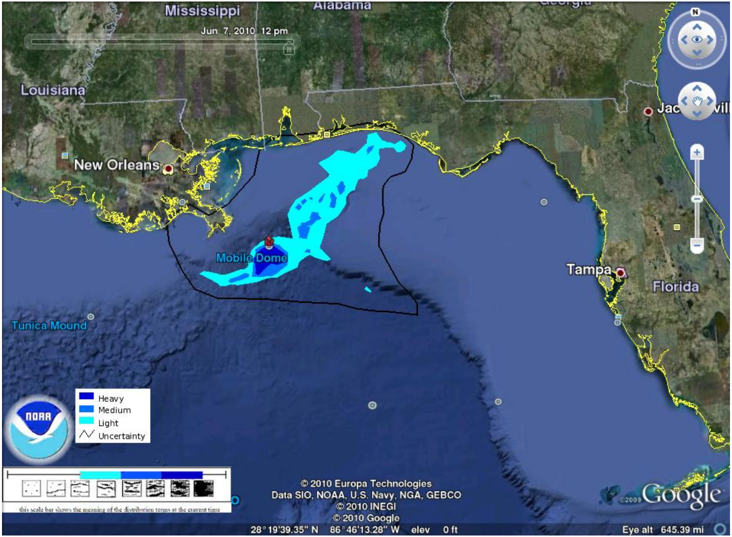
SenSys 2010, Zurich, Switzerland

Motivation: Underwater Sensing

- BP oil spill – riser pipe

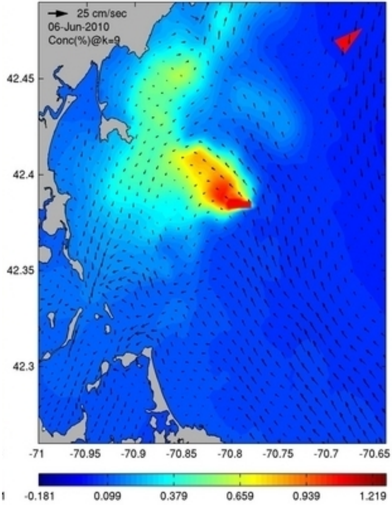
Image from reuters.com

Motivation: Underwater Sensing



- BP oil spill – extent is unknown

Motivation: Underwater Sensing



- Boston Harbor sewer pipe output

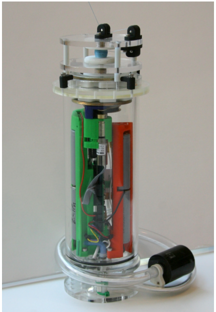
Image courtesy Mingshun Jiang, UMass Boston

System Approach

- Many inexpensive sensors
- Networked for real-time feedback
- Collaborate with robot
- Adjust depth for sensing using decentralized depth control algorithm (*this talk*)

Depth adjustment enables:

- Easy deployment
- Easy recovery
- GPS or radio on surface
- Optimizing position for:
  - Sensing
  - Communication



Related Work

Water column profilers

- Glenn *et al.*. The leo-15 costal cabled observatory – phase II for the next evolutionary decade of oceanography. Scientific Submarine Cable, 2006.
- Howe and McGinnis. Sensor networks for cabled ocean observatories. International Symposium on Underwater Technology, 2004.
- Joeris. A horizontal sampler for collection of water samples near the bottom. Limnology and Oceanography, 1964.

Coverage and sensor placement

- Bullo, Cortés, and Mortínez. Distributed Control of Robotic Networks. Applied Mathematics Series. Princeton University Press, 2009.
- Guestrin, Krause, and Singh. Near-optimal sensor placements in gaussian processes. International Conference on Machine Learning, 2005.
- Ko, Lee, and Queyranne. An exact algorithm for maximum entropy sampling. Operations Research, 1995.
- Schwager, Rus, Slotine. Decentralized, adaptive coverage control for networked robots. IJRR, 2009.

Simulated underwater depth adjustment algorithms

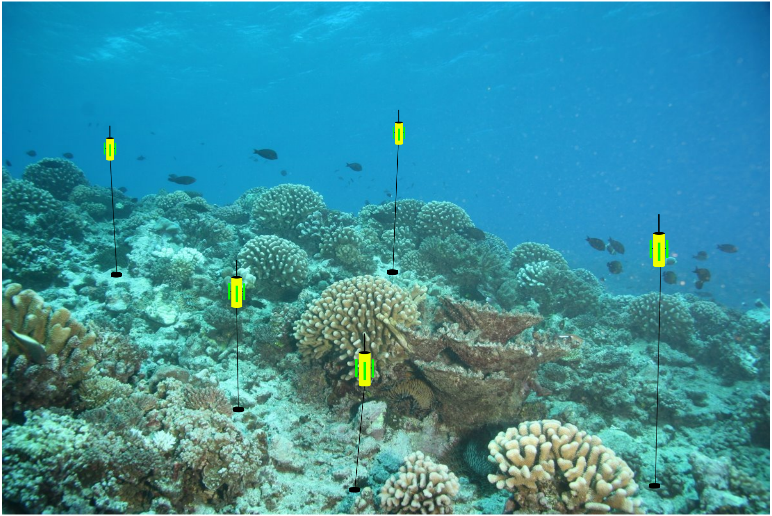
- Akyildiz, Pompili, and Melodia. State-of-the-art in protocol research for underwater acoustic sensor networks. WUWNet, 2006.
- Cayirci, Tezcan, Dogan, and Coskun. Wireless sensor networks for underwater survelliance systems. Ad Hoc Networks, 2006.

Related areas

- Drifting floats
- AUVs adjusting relative positions

Outline

Communication



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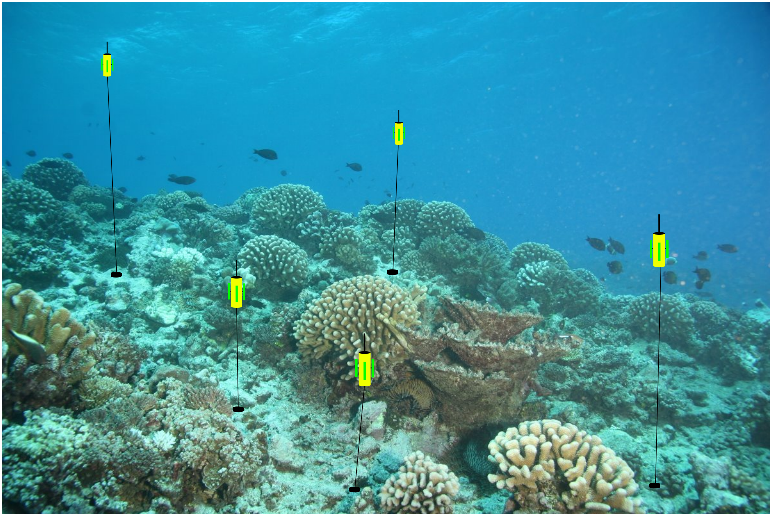

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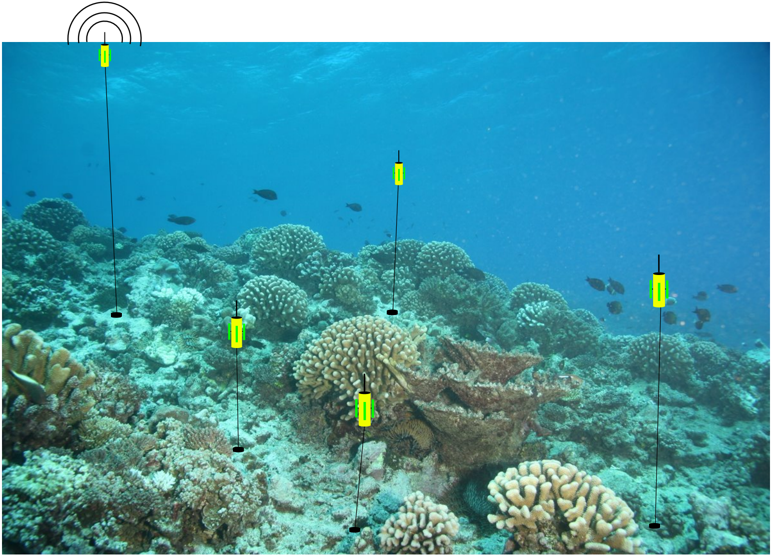

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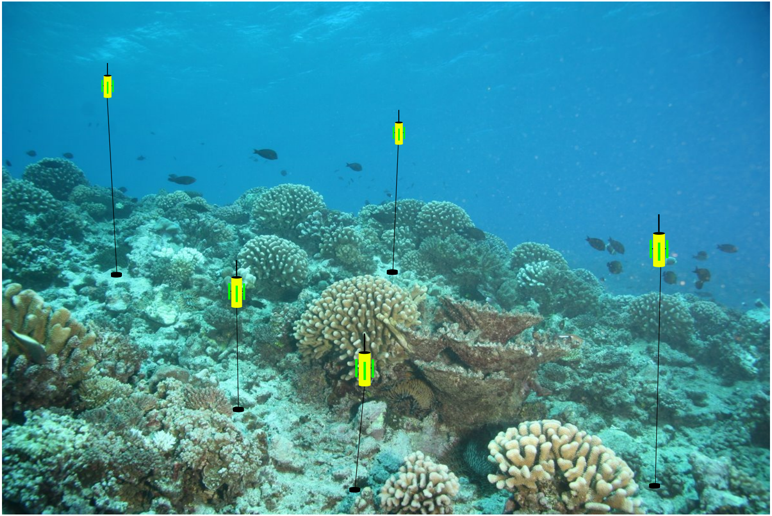

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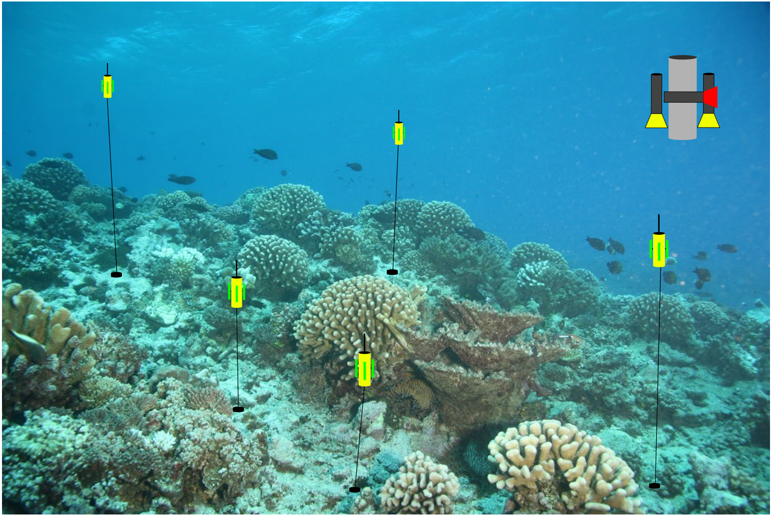

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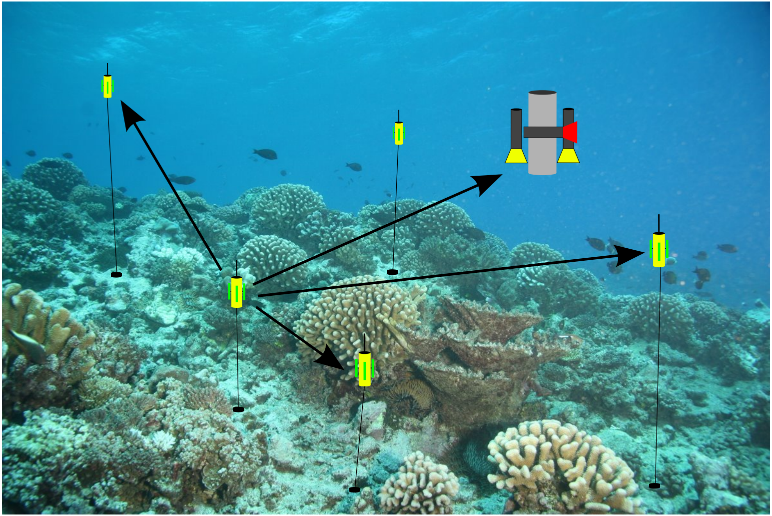

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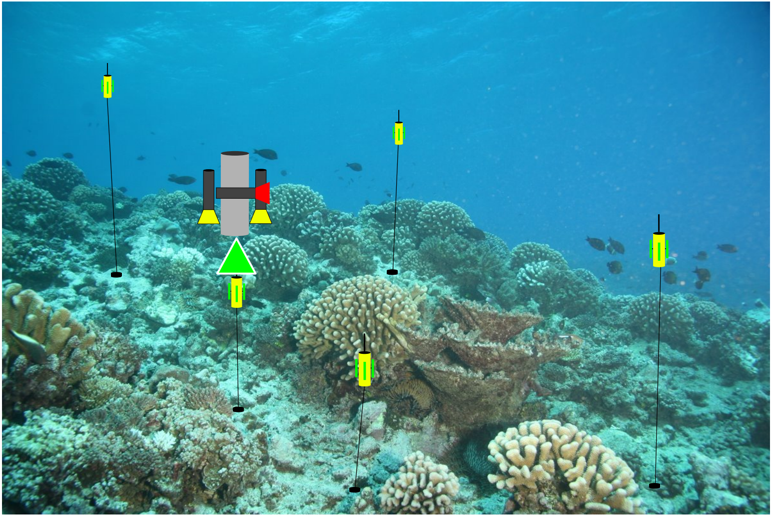

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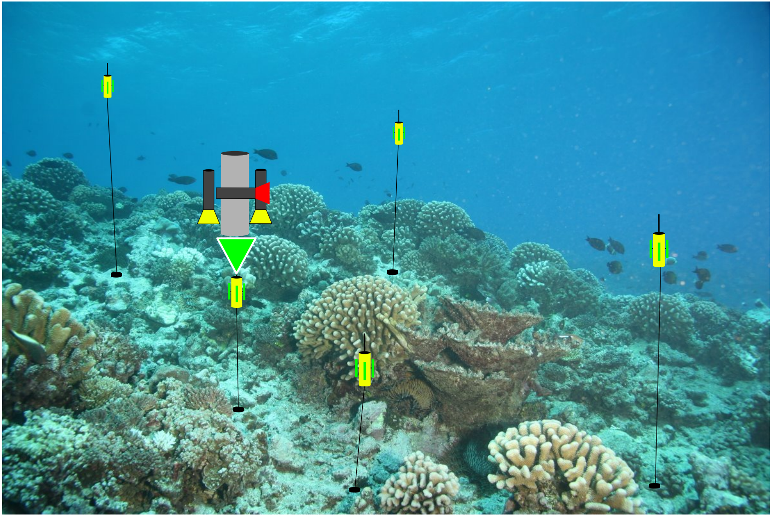

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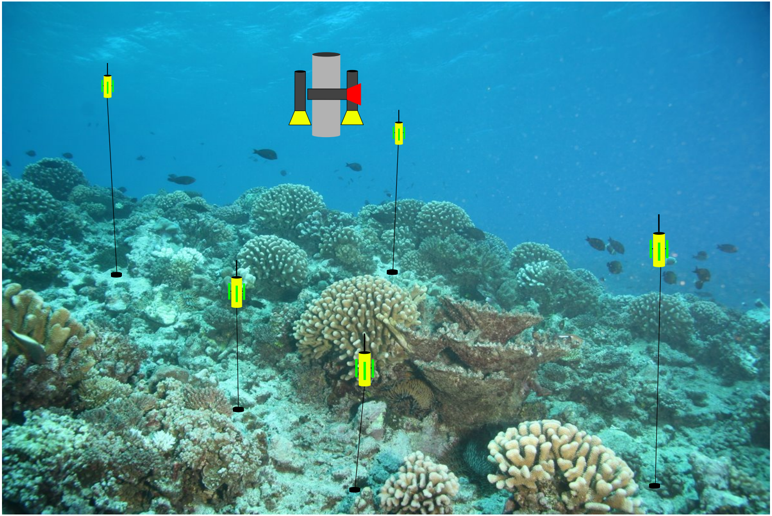
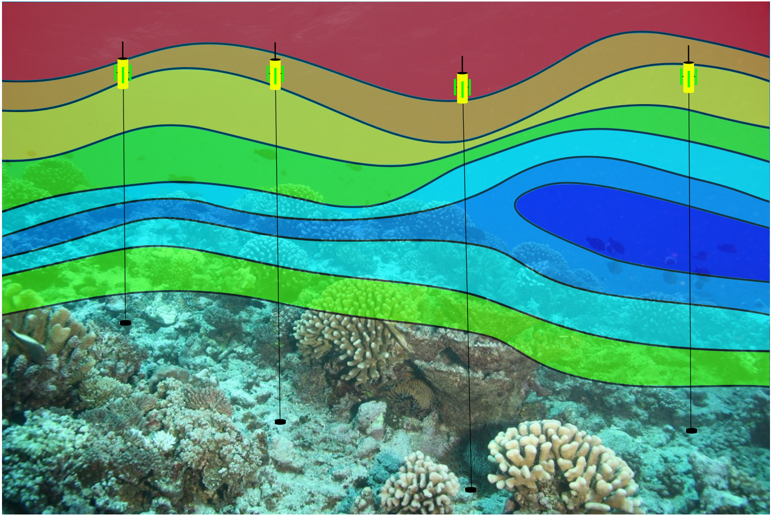


Improving Sensing



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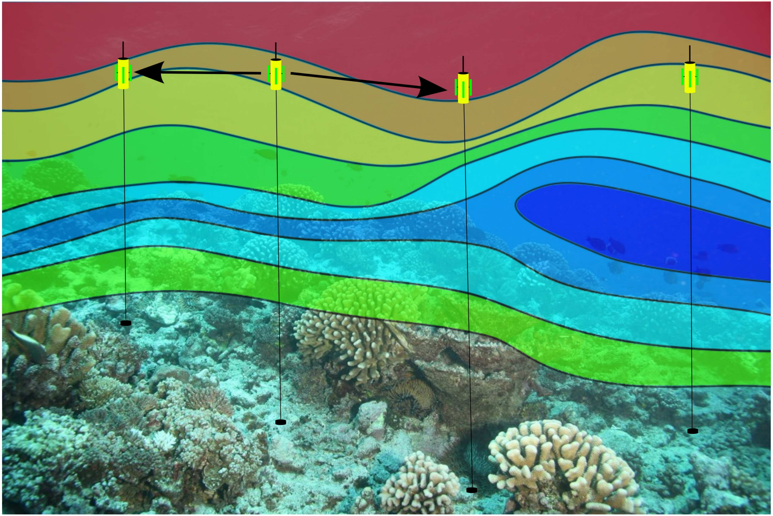

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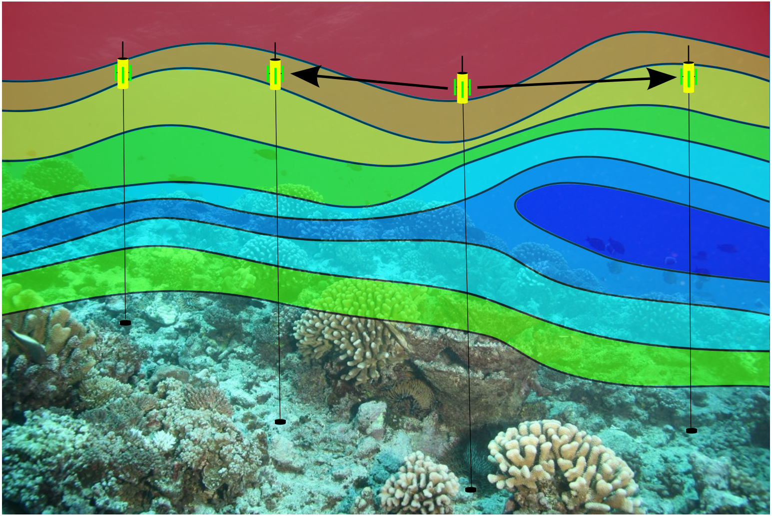

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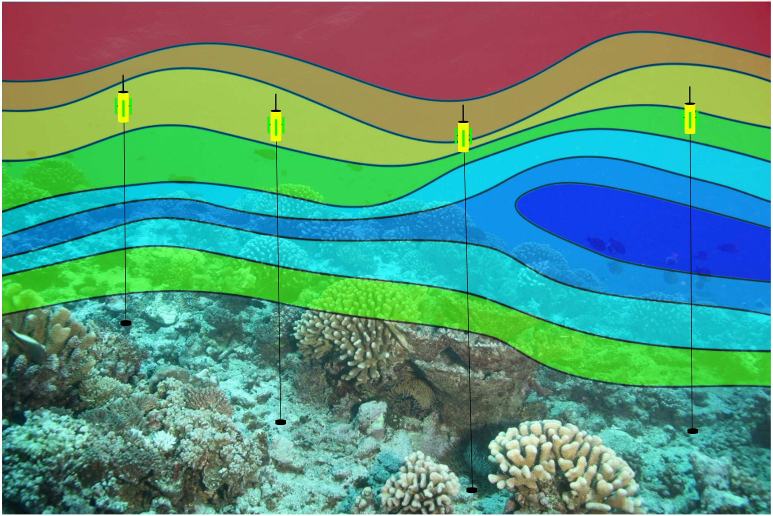

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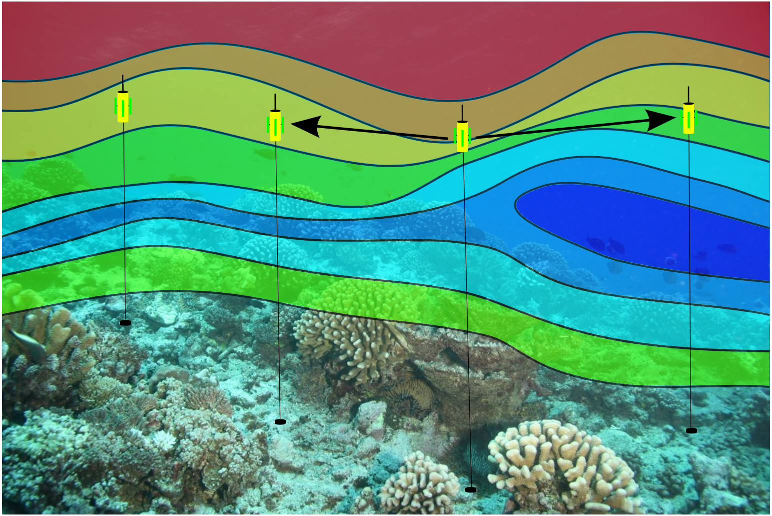

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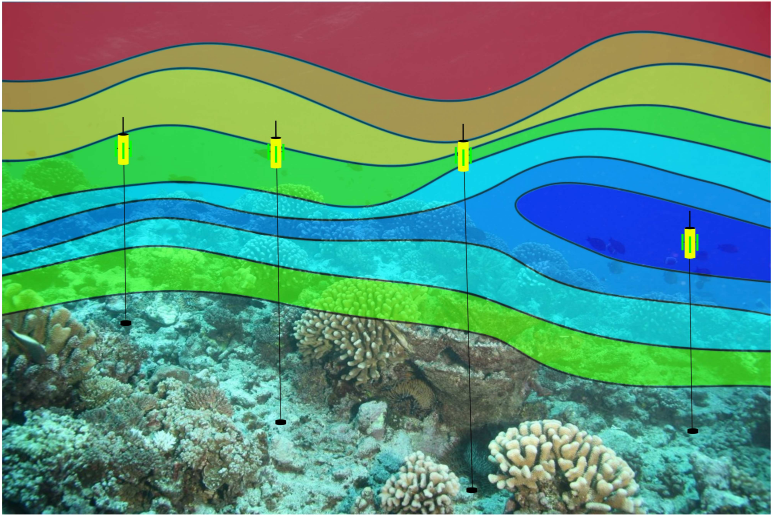

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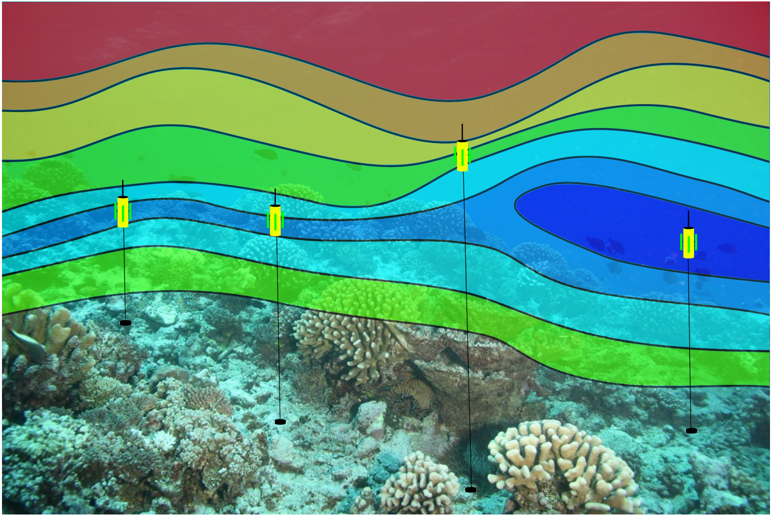
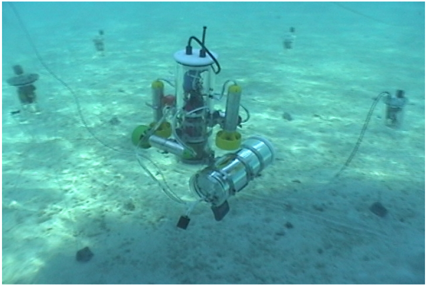


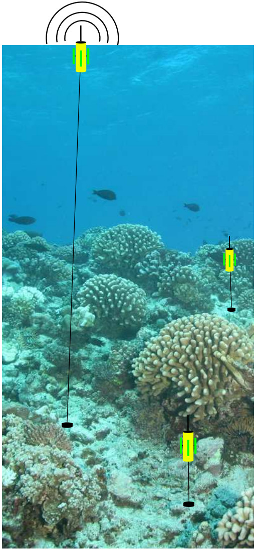
Contributions

- Decentralized depth control algorithm
- Optmizes depths for sensing
- Based on covariance measurements
- Provable convergence
- Low processing and communication
- Tested in simulation
- Implemented and tested on AquaNodes



Decentralized Depth Adjustment for Improved Sensing

- Measurement of water column properties
  - Temperature, salinity, pH, dissolved O_2, etc.
  - Images
- Capture time-varying properties
- Constraints
  - Power
    - Minimize motion
    - Minimize communication
  - Acoustic communication bandwidth
    - 11 bytes per packet
  - Transmit just position, depth, and sensor reading



Covariance

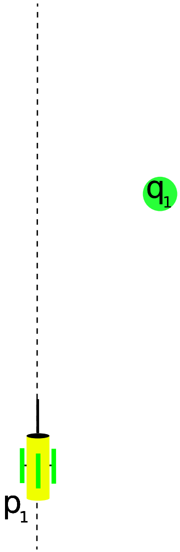
- Measure q_1 from constrained path
- Changes at q_1 correlated to changes at p_1
- Highest correlation when p_1 close to q_1:

$$Min(Dist(q_1, p_1))$$

- More generally use covariance:

$$Max(Cov(q_1, p_1))$$

- Allows different sensing functions



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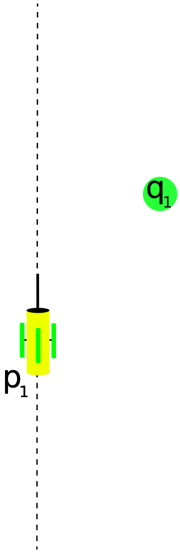

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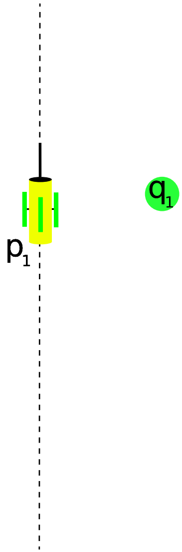
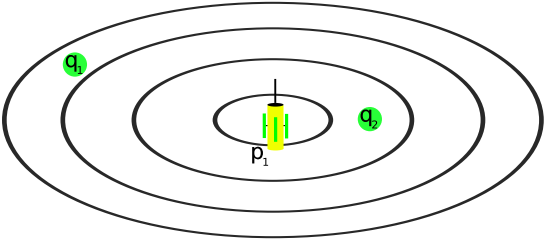
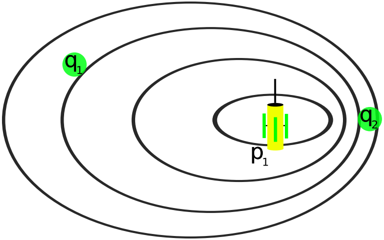


Covariance Model



- Assume Gaussian
- Different variance along surface
- Better models with more knowledge

Covariance Model



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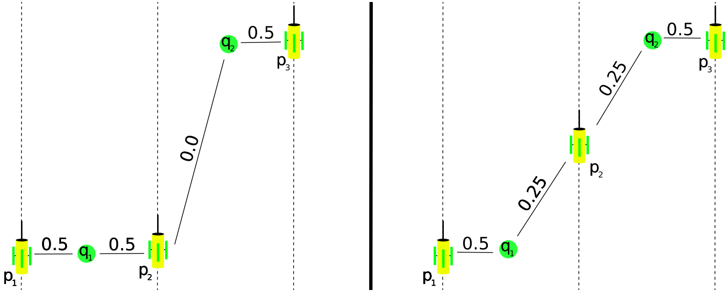
Multiple Points Problem



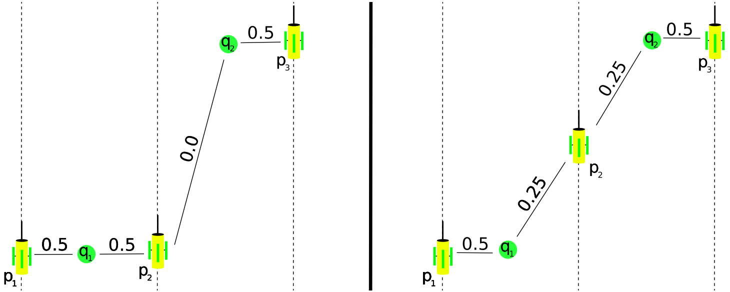
- Idea: maximize sum over whole region:

$$\sum_{Q} \sum_{i=1}^{N} Cov(q, p_i)$$

- Problem: left and right are same:

$.5 + .5 + .5 = 1.5$ $\quad$ $.25 + .25 + .5 + .5 = 1.5$

Multiple Points Solution



- Solution: invert sum of covariance and minimize

$$\sum_{Q} \left(\sum_{i=1}^{N} Cov(q, p_i) \right)^{-1}$$

- Yields:

$\frac{1}{.5+.5} + \frac{1}{.5} = 3$ $\quad\quad$ $\frac{1}{.5+.25} + \frac{1}{.5+.25} = 2\frac{2}{3}$

Algorithm Approach

- Objective function:

$$\mathcal{H}(p_1, ..., p_N) = \int_Q \left(\sum_{i=1}^{N} Cov(q, p_i) \right)^{-1} dq$$

- Decentralized gradient controller:

$$\dot{p}_i = -k \frac{\partial \mathcal{H}}{\partial z_i}$$

$$\frac{\partial \mathcal{H}}{\partial z_i} = \int_Q g(q, p_1, ..., p_N)^2 f(p_i, q) \frac{(z_i - z_q)}{\sigma_d^2} dq$$

$$g(q, p_1, ..., p_N) = \left(\sum_{i=1}^{N} f(p_i, q) \right)^{-1}$$

$$f(p_i, q) = Cov(p_i, q) = Ae^{-\left(\frac{(x_i - x_q)^2 + (y_i - y_q)^2}{2\sigma_s^2} + \frac{(z_i - z_q)^2}{2\sigma_d^2} \right)}$$

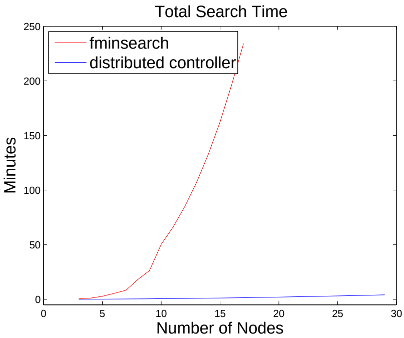
Algorithm Convergence

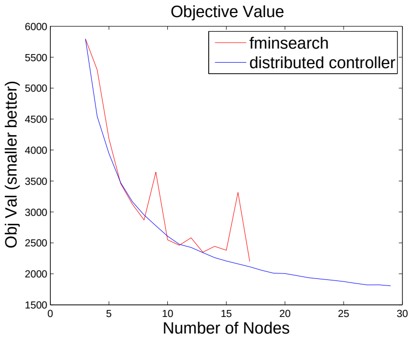
- Each node moves according to:

$$\dot{p}_i = -k\frac{\partial \mathcal{H}}{\partial z_i}$$

- Theorem: decentralized controller converges to local minimum
- Proof: convergence proof using Lyapunov criteria
  - $\mathcal{H}$ must be differentiable;
  - $\frac{\partial \mathcal{H}}{\partial z_i}$ must be locally Lipschitz;
  - $\mathcal{H}$ must have a lower bound;
  - $\mathcal{H}$ must be radially unbounded or the trajectories of the system must be bounded.
- Verified in simulation, pool, and river experiments

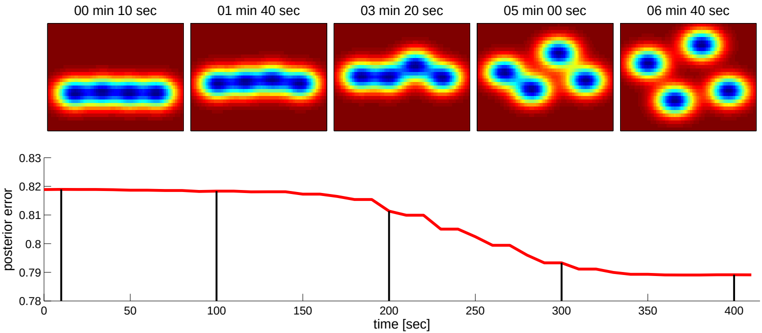
Simulation Results: Versus Matlab's fminsearch





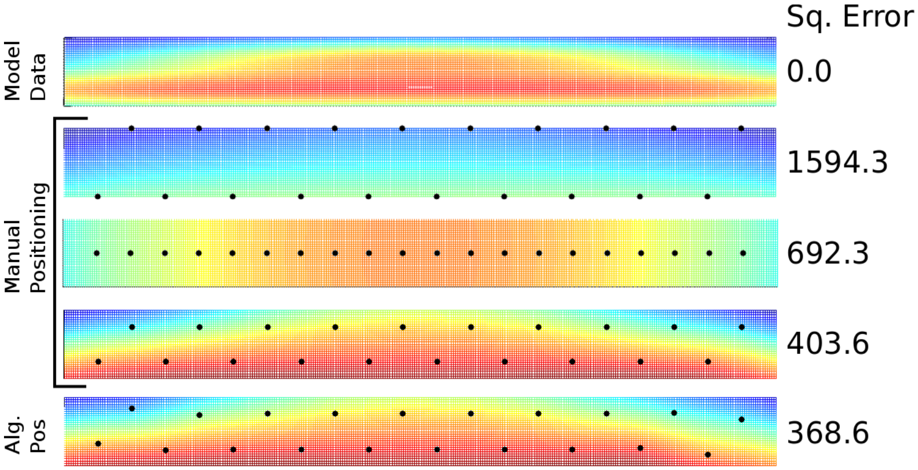
- fminsearch: Matlab's nonlinear unconstrained solver
- Much faster runtime
- Typically lower objective value

Posterior Variance



- Posterior variance
  - Variance given sensor positions, assuming Gaussian process
  - $\sigma^2_{q|P} = Cov(q,q) - \Sigma_{q,P} \cdot \Sigma^{-1}_{P,P} \cdot \Sigma_{P,q}$
  - Requires matrix inversion ($O(n^2)$ memory for n sensors)
- Decentralized depth control algorithm
  - Tends to reduce posterior error
  - Constant memory requirements

Simulation Results: Data Reconstruction



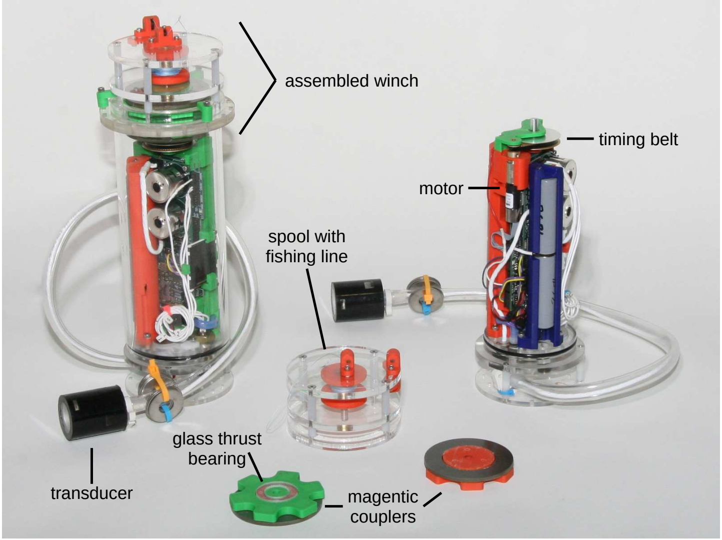
Top row: Original data Bottom row: Depth adjustment algorithm

Outline

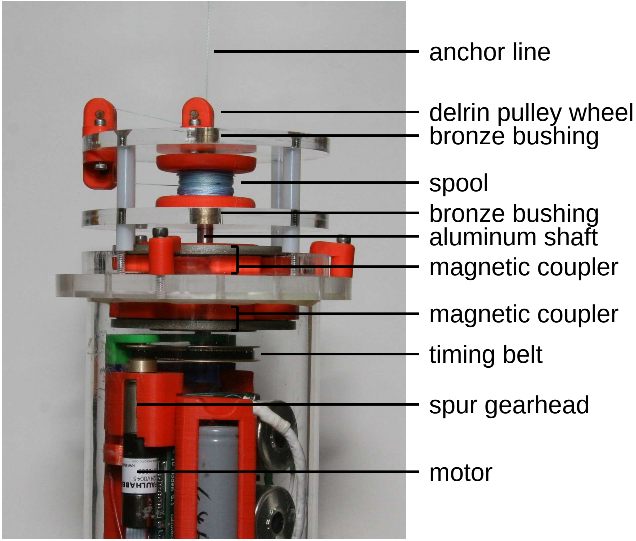
Underwater Sensor Network: AquaNodes

- Multi-purpose underwater sensor network
- Acoustic, optical, and radio communication
- Easy to use and deploy
- Dynamic depth adjustment

Dynamic Depth Adjustment



Dynamic Depth Adjustment

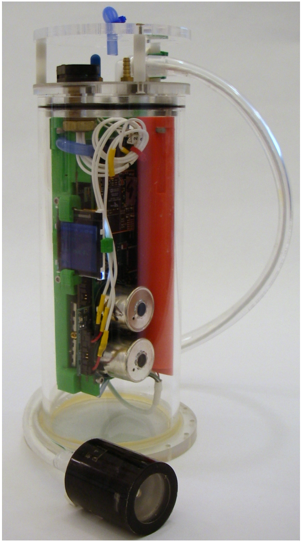


Dynamic Depth Adjustment

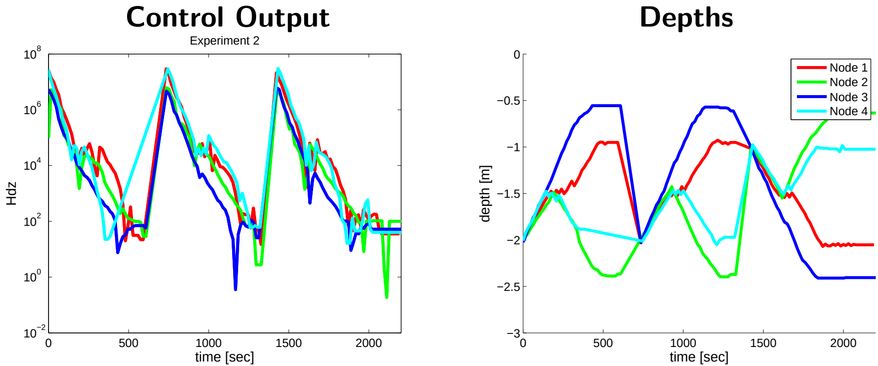
Video: Winch in Pool

AquaNodes: Platform Overview

- LPC2148 60MHz ARM7
- SD Card for logging
- Temperature, pressure, CDOM, salinity, dissolved 0_2, camera
- Digital and analog inputs
- Depth adjustment: 2.4m/min
- Communications
  - Acoustic (FSK modulation): 300b/s up to 200m
  - Radio (1W 900MHz Aerocomm): 57kb/s up to 1km on surface
  - Optical (DPIM modulation): 3Mb/s up to 5m



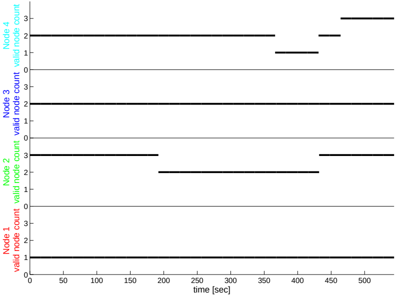
Decentralized Depth Adjustment Results



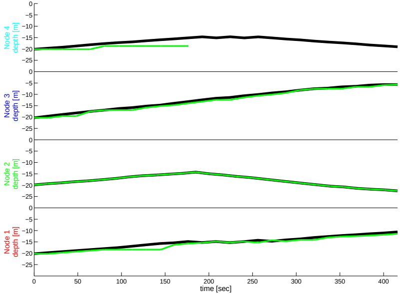
- Four AquaNodes running depth control algorithm in pool
- Three iterations of depth control algorithm
- Algorithm converges within 10 minutes
- Nodes spread out

Decentralized Depth Adjustment Communication

Number of Neighbor

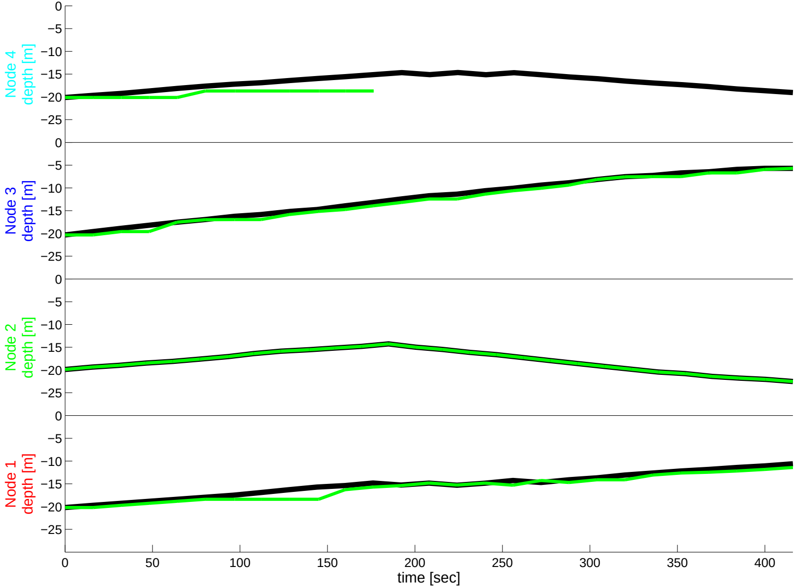


Depth

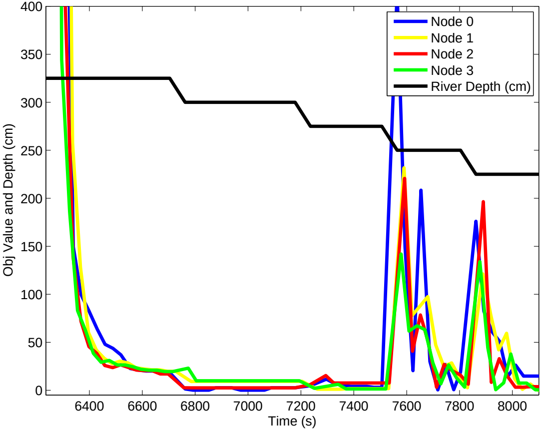


- Communication data from part of previous experiment (4 nodes)
- Nodes do not hear all other nodes
- Algorithm handles communication dropouts

Decentralized Depth Adjustment Communication



Changing Covariance



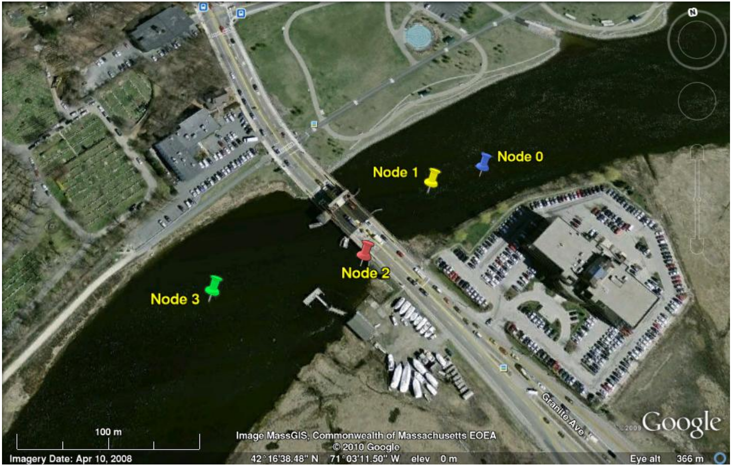
- Changing covariance over time
- For example tidal changes
- Objective value returns to minimum after algorithm adjusts

Outline

Future Work

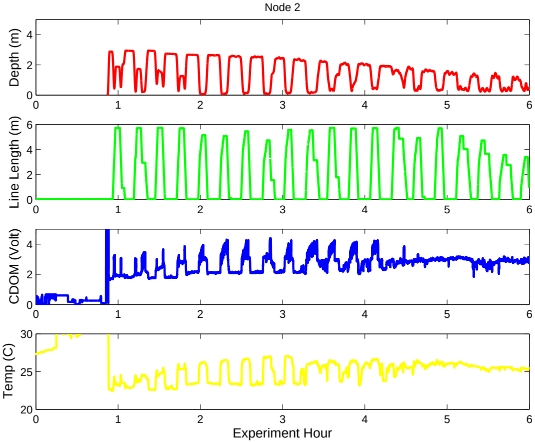
- Collect scientific data
- Long-term deployments
- Determine maximum water current
- Examine impact of bio-fouling
- Leverage depth adjustment for other applications
    - Optimize Acoustic Communication
    - Multi-modal communication (acoustic, radio, optical)

Neponset River Experiment



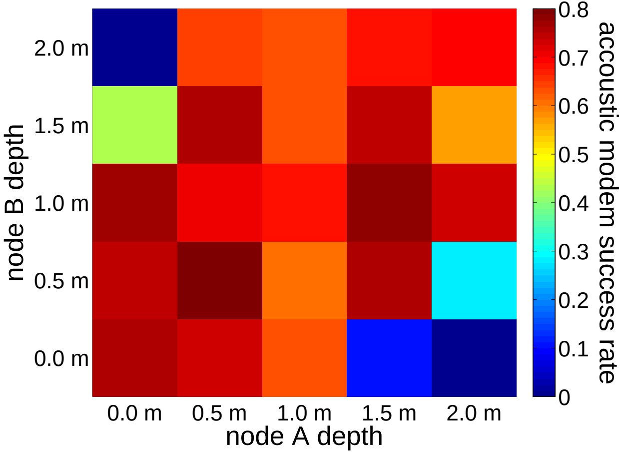
- Summer deployment in Neponset River w/ 4 nodes
- Nodes performed column scans, sensing temp, pressure, CDOM
- Collecting data for future depth optimization experiments

Neponset River Experiment



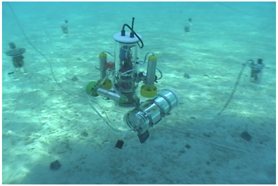
- Deployment for half tidal cycle

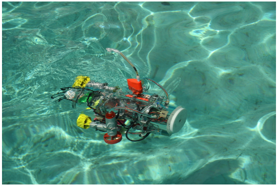
Acoustic Communication Example



- Placement is critical for acoustic comms
- Short-range river experiment between walls

Contributions and Conclusions



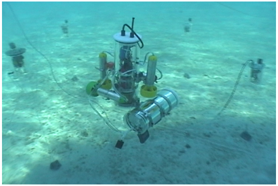


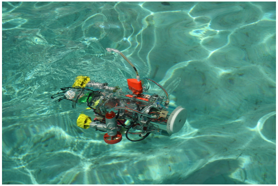
- Algorithms in an underwater sensor network
  - Decentralized depth control for sensing
    - Provable convergence
  - Verified in simulation and field experiments
- System implementation and experiments
  - Underwater sensor network
  - Dynamic depth adjustment
  - Tested in pools, lakes, and rivers
- Future work taking advantage of depth adjustment
- Leverage sensor networks to improve environmental understanding

contact me at: carrick@cse.unl.edu

http://cse.unl.edu/∼carrick

Questions?





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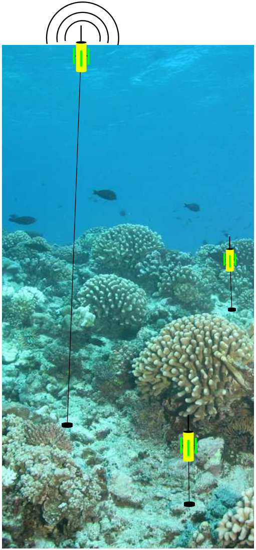
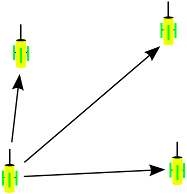
Outline All

Radio Communication



- Uses winch to go to surface
- 900MHz Aerocomm radio
- Built-in broadcast protocol
- 1 Watt transmit power
- 20km max range
- 1km typical range

Acoustic Communication



- Developed in our lab
- Broadcast protocol
- 600MHz DSP
- 27-33 KHz
- Frequency-Shift Keying (FSK)
- 300b/s
- 45mJ/bit (2W transmit power)
- 400m range
- Ranging between modems
  - 4cm resolution
- Time Division Multiple Access (TDMA)
  - Self-synchronizing

Optical Communication

- Developed in our lab
- Point-to-Point
- 5 meter 90° cone
- 3Mbit/s
- 7μJ/bit
- 532nm wavelength (green)
- Digital Pulse Interval Modulation (DPIM) modulation