Informative sensing using multiple robots for environmental applications

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Introduction:

Challenges in environmental sensing

- **Large spatial coverage and dynamic temporal variation**
- **Prohibitively expensive to use static sensing**
- **Motivates the use of actuated sensors – mobile robots carrying environmental sensors**
- ***Constraint:* Limited fuel capacity of mobile robots**
- ***Fundamental Problem:* Where should we sample a phenomenon to maximize the collected information?**
- **Example: Growth pattern of phytoplankton in a lake**

How to quantify collected information?

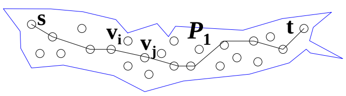
- **Model the phenomenon as Gaussian Process (GP)**
- **Use Mutual Information (MI) as the objective function**
  - Measures the reduction in uncertainty (entropy) at unobserved locations

$$MI(\mathcal{P}) = H(\mathcal{X}_{\mathcal{V}\setminus\mathcal{P}}) - H(\mathcal{X}_{\mathcal{V}\setminus\mathcal{P}}|\mathcal{X}_{\mathcal{P}})$$

$H(\mathcal{X}_{\mathcal{V}\setminus\mathcal{P}})$: Entropy of unobserved locations

$H(\mathcal{X}_{\mathcal{V}\setminus\mathcal{P}}|\mathcal{X}_{\mathcal{P}})$: Conditional entropy after sensing at $\mathcal{P}$ (chosen path)

Multi-robot Informative Path Planning(MIPP) problem



Sensing cost $C(v) > 0$; Traveling cost $C(v_i, v_j)$

$$C(\mathcal{P}_1) = \sum_i C(v_i) + \sum_{i,j} C(v_i, v_j)\ \forall\, v_i, v_j \in \mathcal{P}_1,\ C(\mathcal{P}_1) \le B$$

- **For a collection of *k* paths, $\mathcal{P} = \mathcal{P}_1 \cup \mathcal{P}_2 \cup .. \mathcal{P}_k$, let MI ($\mathcal{P}$) be the mutual information collected by all the paths**

- **Formally, MIPP can be defined as:**

$$\max_{\mathcal{P} \subset \mathcal{V}} MI(\mathcal{P})$$

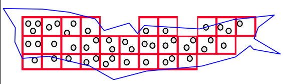
$$\textit{subject to } C(\mathcal{P}_i) \le B, \forall\, i \le k$$

- **We propose *sequential-allocation* algorithm that provides strong approximation guarantee for MIPP**
  - $(1 + \eta)$ with η being the approximation guarantee of any single robot instance of informative path planning
  - Example: $\eta = \log$ (OPT) with OPT = number of nodes in optimal path as proposed in Chekuri et. al, FOCS'05.

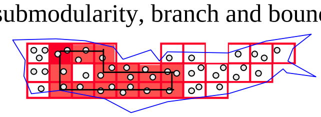
Efficient characterization of environmental applications

Efficient Multi-robot Informative Path planning

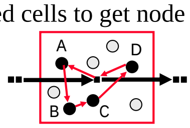
Spatial Decomposition



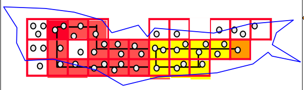
Obtain cell path exploiting submodularity, branch and bound

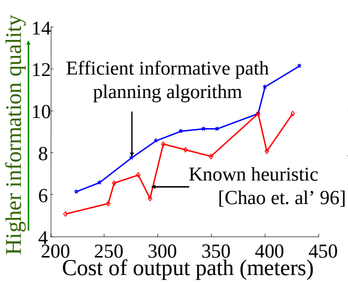


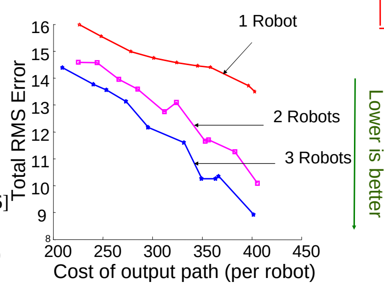
Greedy node selection within visited cells to get node path



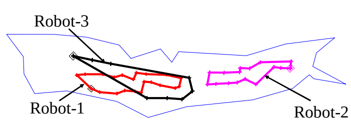
Sequential Allocation for multi-robot path planning



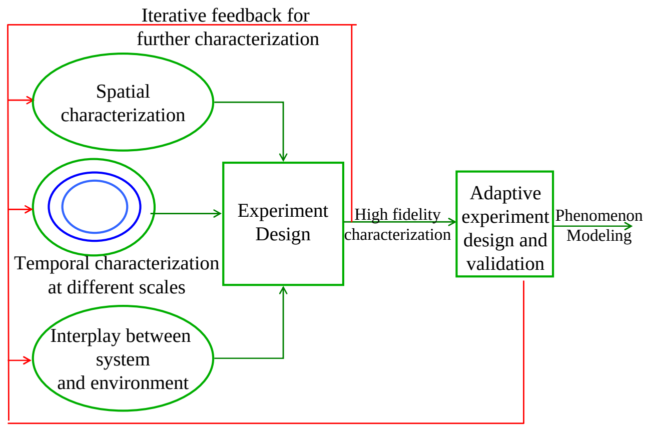


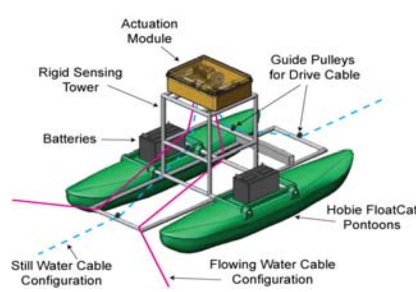


Performance comparison using temperature data collected using robotic boat



Iterative experiment Design for Environmental Applications (IDEA) methodology





Aquatic based Networked InfoMechanical System (NIMS-AQ): An autonomous system used for implementing IDEA and MIPP