TerraSwarm

Efficient Information Acquisition with Mobile Sensors

Penn UNIVERSITY of PENNSYLVANIA

http://terraswarm.org/

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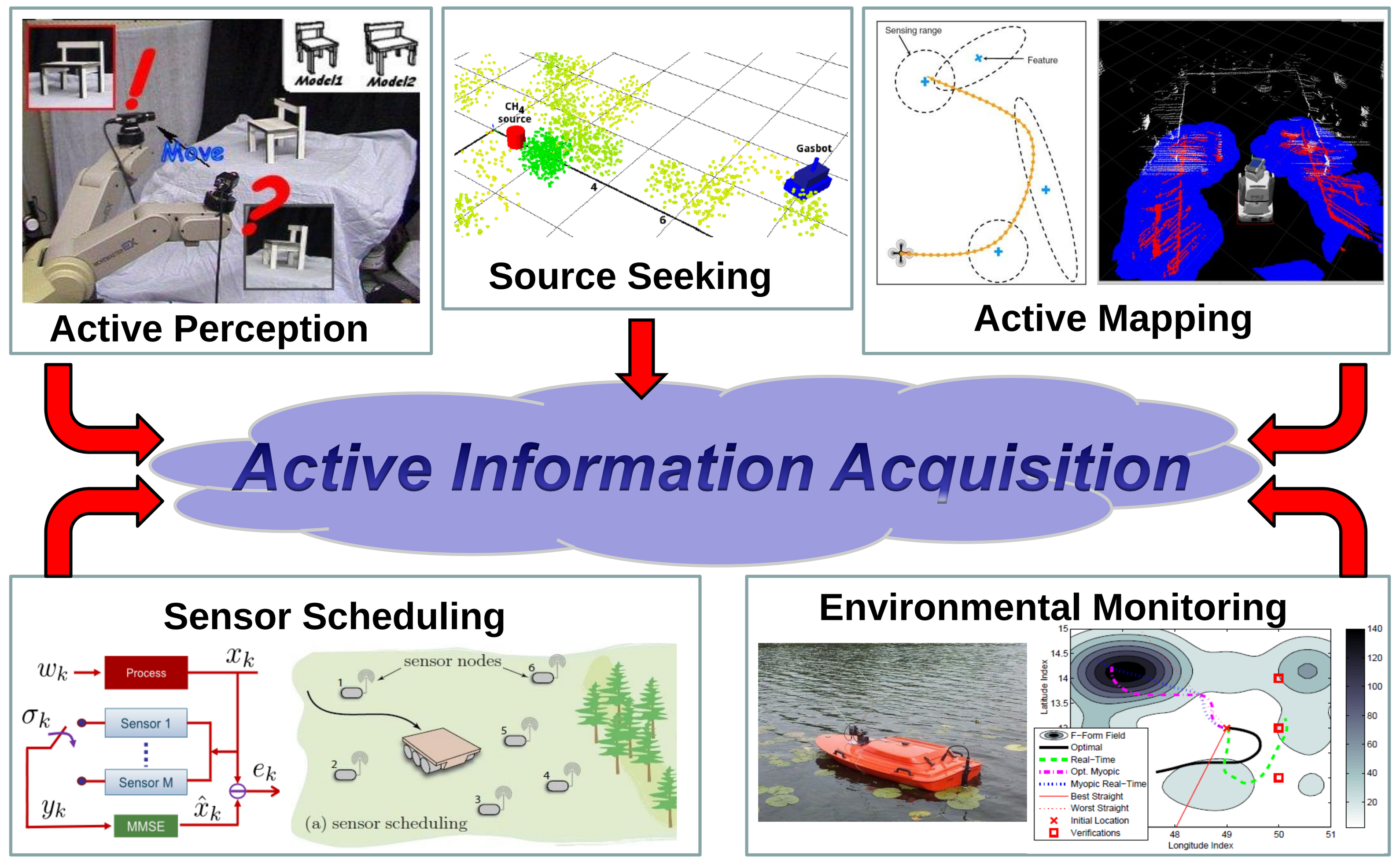


The Objective (Task D.3.3)

Design a scalable control strategy for a swarm of mobile sensors to observe and evolving phenomenon of interest (target) efficiently

Sensor & Target Characteristics

- Sensor Motion Model (SMM): $x_{t+1} = f(x_t, u_t), \quad x_t \in \mathcal{X}, u_t \in \mathcal{U}$
- Target Motion Model (TMM): $y_{t+1} = a(y_t, w_t), \quad y_t \in \mathcal{Y}, w_t = \text{noise}$
- Sensor Observation Model (SOM): $z_t = h(x_t, y_t, v_t), \quad v_t = \text{noise}$

Active Information Acquisition Problem:

Given a finite horizon T, choose a control policy to maximize the ***mutual information*** between the measurements and the final target state: $\max \mathbb{I}(y_T ; z_{1:T} \mid x_{1:T})$

Linear Gaussian Assumptions

- TMM: $y_{t+1} = Ay_t + w_t, \quad y_t \in \mathcal{Y}, w_t \sim \mathcal{N}(0, W)$
- SOM: $z_t = H(x_t)y_t + v_t(x_t), \quad v_t \sim \mathcal{N}(0, V(x_t))$

Separation Principle:

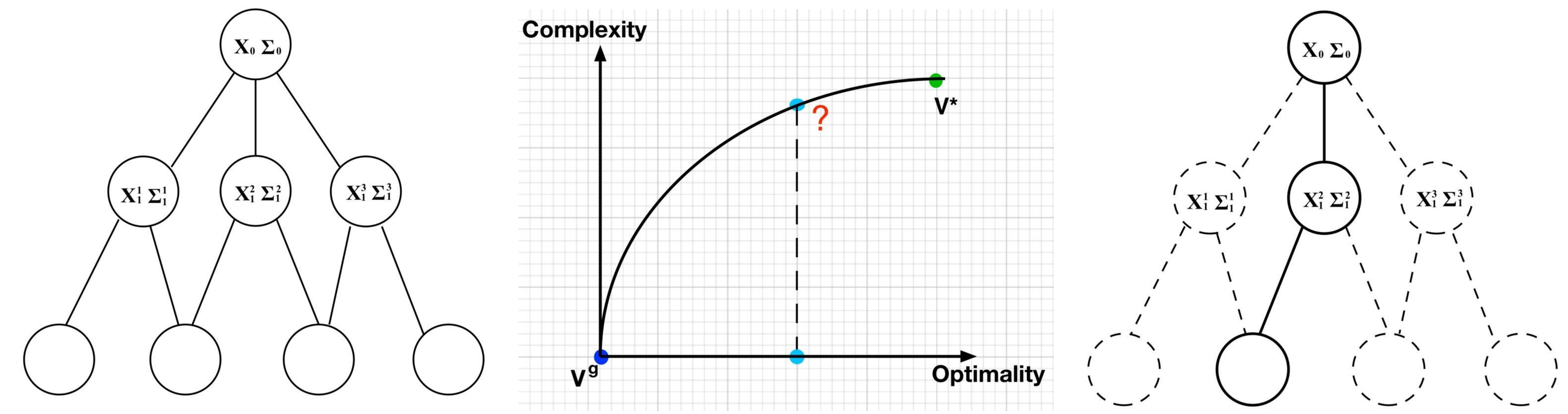
Under linear Gaussian assumptions, open-loop policies are optimal and the problem reduces to a deterministic control problem:

$$\max_{u_0,\ldots,u_{T-1}} \log\det(\Sigma_T)$$
$$\text{s.t.} \quad x_{t+1} = f(x_t, u_t), \quad t = 0,\ldots,T-1,$$
$$\Sigma_{t+1} = \rho(\Sigma_t, x_{t+1}), \quad t = 0,\ldots,T-1,$$

Σ is the covariance of the target distribution, ρ is the Riccati map

Forward Value Iteration:
- keeps all reachable nodes
- obtains optimal solution

Greedy policy:
- keeps only the best node per stage
- no sub-optimality guarantees

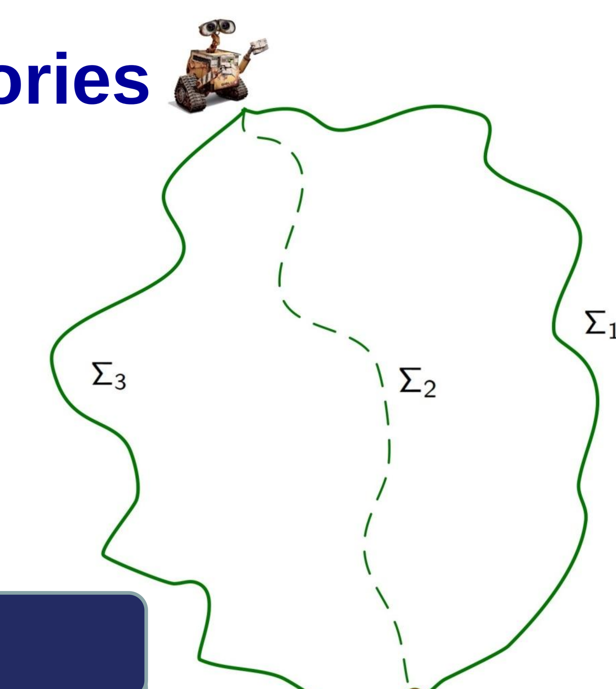


What about the middle ground?

Partial Order on Sensor Trajectories

Algebraic Redundancy:

$\Sigma \in S_+^n$ is algebraically redundant wrt $\{\Sigma_k\}_{k=1}^K \subset S_+^n$ when $\Sigma \succeq \sum_{k=1}^K \alpha_k \Sigma_k$ for some non-negative constants $\{\alpha_k\}$, which sum to 1.



$\Sigma_2 \succeq \alpha\Sigma_1 + (1-\alpha)\Sigma_3$

Theorem:

For some $t \in [1,T]$, let $(x,\Sigma) \in S_t$ be a node in the t-th level of the search tree. If there exists a set $\{x^i, \Sigma^i\} \subseteq S_t \setminus \{(x,\Sigma)\}$ such that:

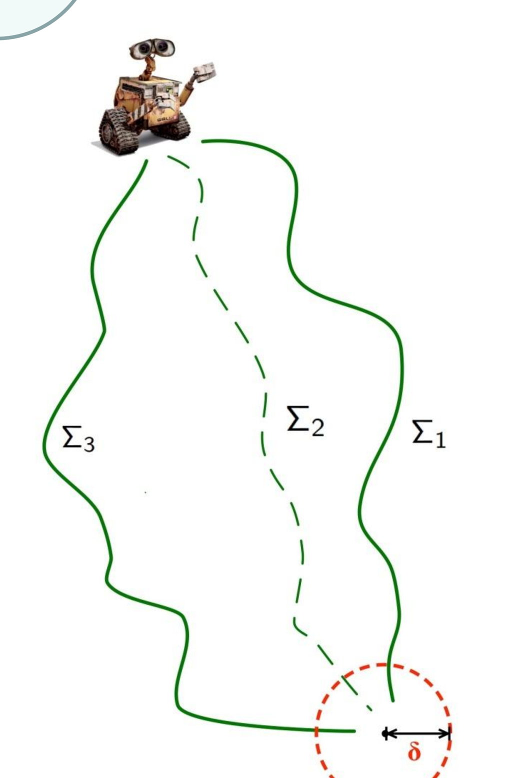
$x = x^i, \quad \forall i$

Σ is algebraically-redundant with respect to $\{\Sigma^i\}$,

then (x,Σ) can be removed from S_t without eliminating the optimal sensor path.

Relaxing the Conditions

- Remove paths which are:
  - almost crossing at time t
  - almost algebraically-redundant paths
- Regularity assumptions are necessary



$\Sigma_2 + \epsilon I \succeq \alpha\Sigma_1 + (1-\alpha)\Sigma_3$

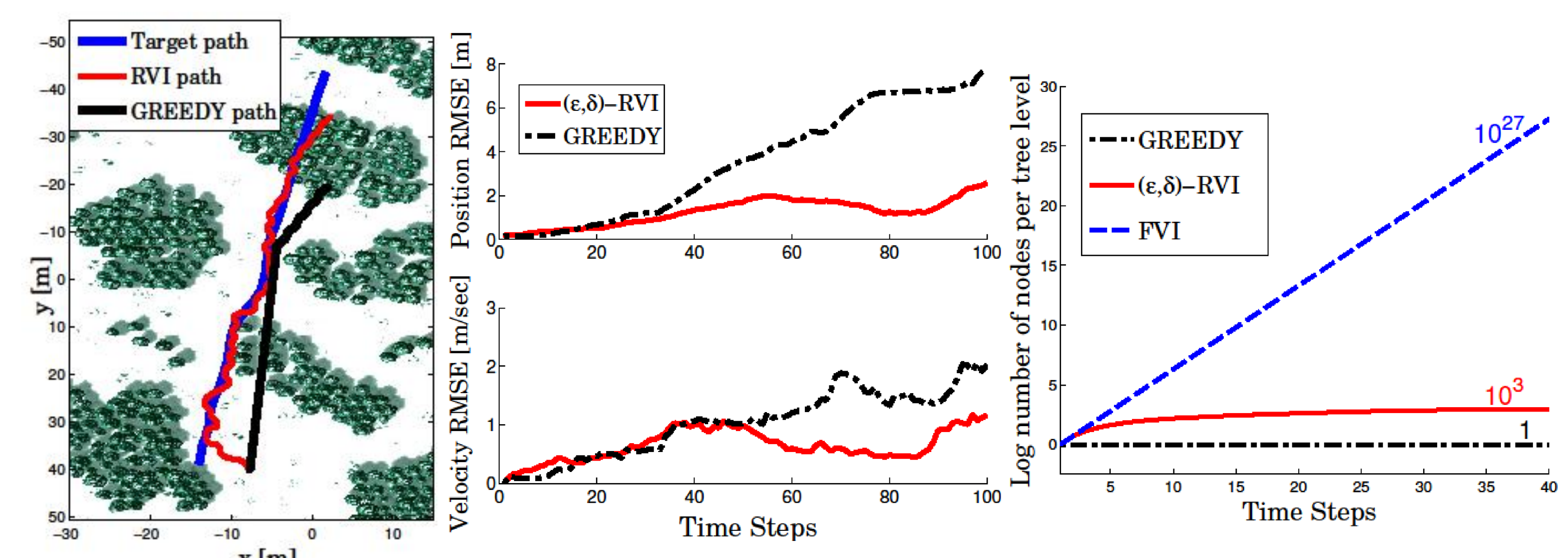
Theorem:

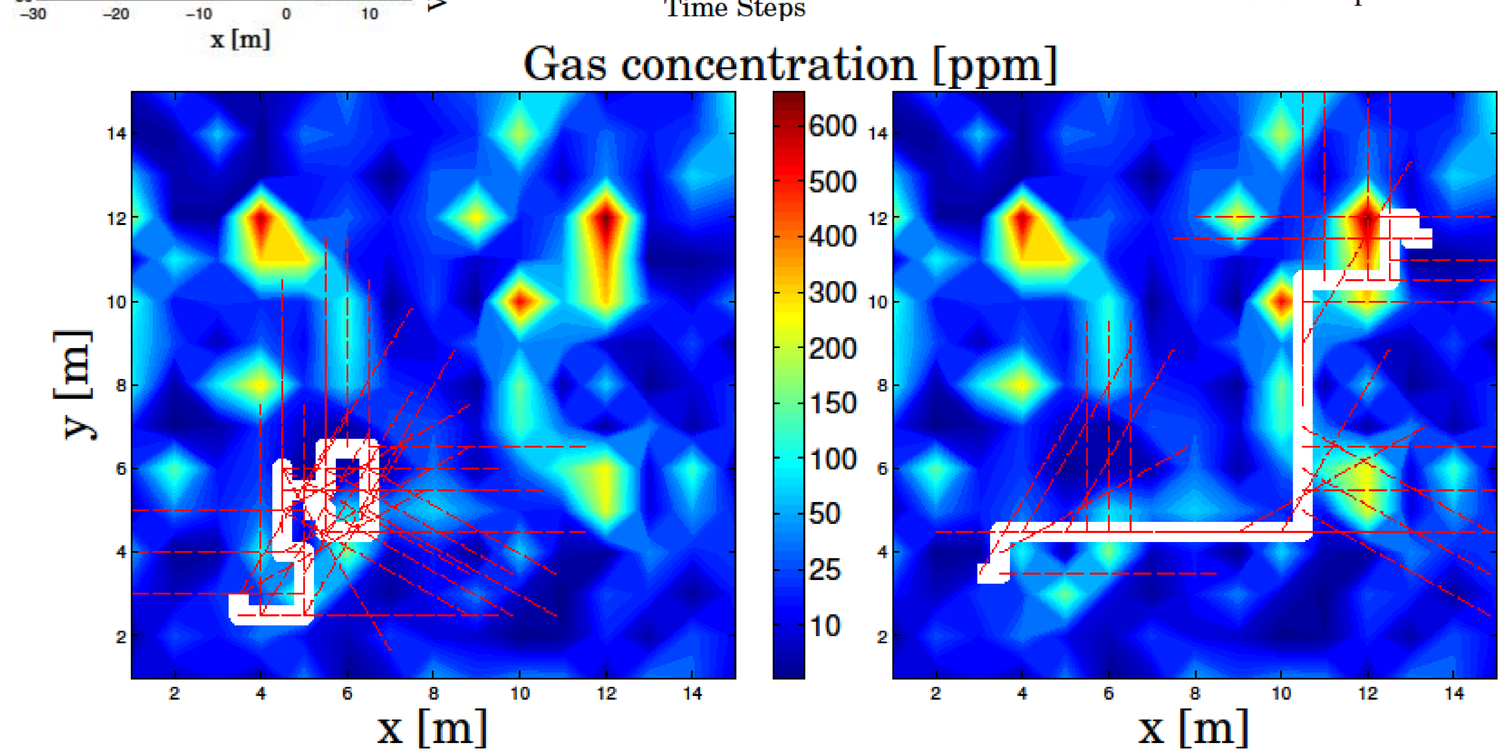
The sub-optimality gap between the cost V_T^* of the optimal sensor path and the cost $V_T^{\epsilon,\delta}$ of the path obtained after the reductions satisfies:

$$0 \le V_T^{\epsilon,\delta} - V_T^* \le (\Gamma_T^\delta - 1)(V_T^* - \log\det(W)) + \epsilon\Delta_T^\delta$$

Our Contribution

- Non-myopic control strategy for mobile sensors with linear Gaussian observation models to track targets with linear Gaussian dynamics
  - Sub-optimality guarantees on the performance
  - Considers sensor dynamics & continuous space of configurations
  - Trade-off between computation and optimality via the parameters
  - Provably better than the widely used greedy control policy
- Linearization & Model Predictive Control to obtain closed-loop control policy for sensors with non-linear observation models
- Target state inference is still done with a non-linear estimator





Future Direction

- Distributed control and estimation:
  - Estimation from local observations and interaction with neighbors
  - Choose controls locally, while maintaining performance guarantees
- Applications & experimental validation in the Smart City testbed
- Applications with more general sensing models such as active semantic localization
- Distributed self-localization method with consistency guarantees
  - Collaborate with others working on localization (Task D.3.2)

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