Gaussian Processes in Autonomy
Adaptive Control and Adaptive Sensing

Robert Grande

Aerospace Controls Laboratory
Department of Aeronautics & Astronautics
Massachusetts Institute of Technology

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Outline

1. Gaussian Processes
2. Adaptive Sensing
3. Model Reference Adaptive Control
4. Future Work

Gaussian Processes

- Framework exists for nonlinear regression known as Gaussian Processes (GPs)
- Nonparametric approach which models function as correlation between points
  - Underlying structure can be expressed more freely from data
- $p(\mathbf{f} \mid \mathbf{X}) = \mathcal{N}(\mathbf{f} \mid 0, K)$, where $K_{ij} = k(\mathbf{x}_i, \mathbf{x}_j)$ is the kernel function
- Large computational burden as data size increases. Requires offline setting or sparsification.

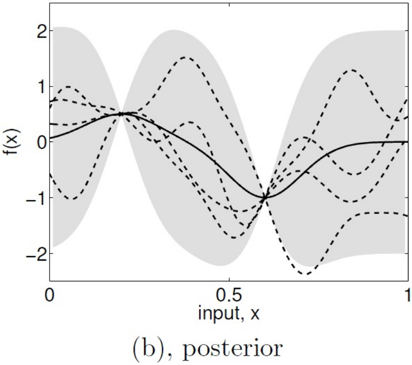


Figure : Posterior estimate given GP assumption

Adaptive Sensing

- Problem statement:
  - Given an unknown environment, find efficient way of choosing informative sensing locations using multiple agents such as UAVs
    - Ex: Plume tracking, modeling flows in lakes, modeling the formation of a thermal in the atmostphere
- Technical Challenges:
  - Choosing the most informative locations requires checking a combinatorial number of grid points, which is intractable
  - Location selection will depend on the modeling parameters, which are unknown
  - Dynamics of the environment may be changing with time
- Past Approaches
  - Use a greedy process to sequentially select most informative points using a GP model.
    - Gives near optimal results, but can be only used for a small subset of problems, known as submodular.

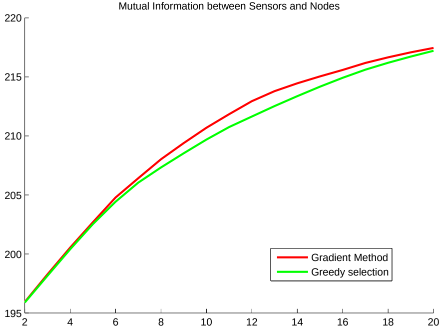
Adaptive Sensing

- Our Approach
  - Use a GP model for efficient selection using closed form expressions
  - Use gradient based optimization
    - Scales comparatively with greedy methods
    - Allows more flexibility in problem definition
  - Training of nonstationary kernel is difficult but results in better waypoint selection
    - Developed method of training nonstationary kernels with significantly reduced computation time

Figure : Toxic Plume from factory fire

Results


Time to convergence
Gradient Method
Greedy selection
0
1
2
3
4
5
6
7
8
9
2
4
6
8
10
12
14
16
18
20


Mutual Information between Sensors and Nodes
Gradient Method
Greedy selection
195
200
205
210
215
220
2
4
6
8
10
12
14
16
18
20

Results

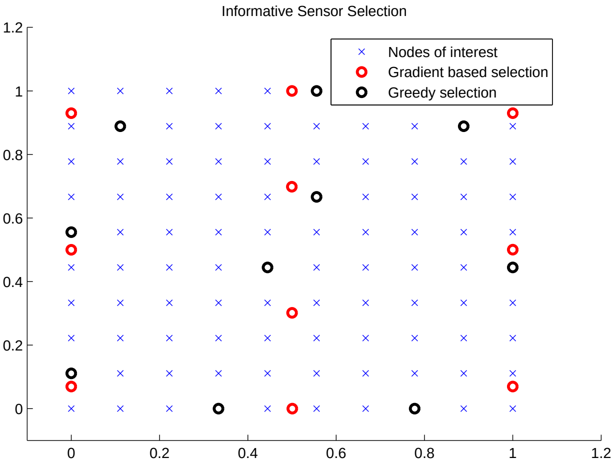


Figure : Comparison of waypoint selection

Research Topic 2: Adaptive Control

Model Reference Adaptive Control

- Goal: control a system with dynamics that are difficult to model or predict
- Typically, two approaches: direct vs. indirect
  - Direct adaptive control attempts to drive tracking error to zero by adjusting control gains directly.
  - Indirect adaptive control models the plant uncertainty and adjusts control according to model.
- In MRAC, popular methods for modeling the uncertainty include the Radial Basis Function -Neural Network (RBFN)
  - Requires a priori knowledge of the operating domain to guarantee coverage
  - Requires tuning of parameters and center locations offline

GP-MRAC Results

- Recently members of the ACL developed new MRAC framework using GPs for regression.
  - Does not require a priori knowledge of the operating domain for domain coverage
- Requires modifications to original GP framework for online feasibility
  - Sparsification and online center allocation for fast prediction

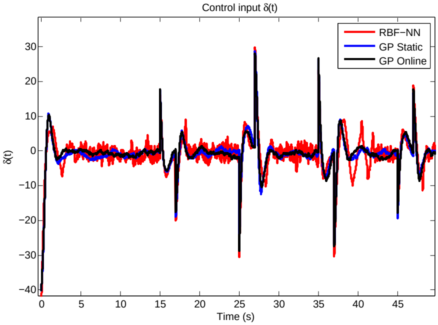


Figure : GP-MRAC models the uncertainty better, leading to smoother control for a case of tracking roll commands subject to wing rock.

CDC 2013 Results

- Submitted paper to the IEEE Conference on Decision and Control 2013
  - Main contribution: Hyperparameter optimization in an online setting
  - Improves robustness of controller to initialization parameters

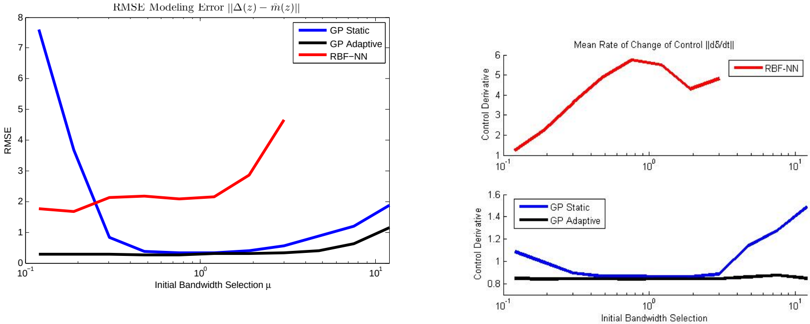


Figure : Hyperparameter optimization results in much more robust control performance for tracking commands subject to wing rock dynamics

Future Work

- Gaussian Processes and Adaptive Sensing
  - Explore performance compared to greedy methods on bench mark examples
  - Need means for fast training of nonstationary kernels in online setting
  - Need way of selecting informative sensing locations with limited a priori information about the structure of the environment
- Adaptive Control
  - Iterative learning: Improve feed forward performance by updating reference model over time or iterations
  - Explorative learning: to learn dynamics efficiently in "safe" conditions using similar criteria from adaptive sensing
  - Test GP-MRAC on more difficult dynamics such as the Hydrodynamic Cart-Pole, aircraft with non-conventional dynamics, etc.

References I