ECE586BH: Interplay between Control and Machine Learning (Fall 2023)

Course Syllabus

Catalog Description: Advanced graduate course focuses on interplay between control and machine learning. One half of the course focuses on tailoring control tools to study algorithms and neural network structures in large-scale machine learning. In the other half of the course, students will study how to combine machine learning and model-based control methods for control design problems.

The following topics will be covered: empirical risk minimization; first-order methods for large-scale machine learning; stochastic optimization; dissipation inequality; jump system theory; Lur'e-Postnikov type Lyapunov functions; integral quadratic constraints; KYP Lemma; graphical interpretations for optimization methods; control-theoretic methods for designing certifiably robust neural networks; control-oriented analysis tools for temporal difference learning and Q-learning; reinforcement learning for linear quadratic regulator (LQR) problems; zeroth-order optimization and evolutionary strategies; policy gradient methods for robust control; Goldstein's subgradient method for H-infinity control; adversarial reinforcement learning; imitation learning for control; regularization of model-free control via prior model-based design; constrained policy optimization.

Course Objectives: Upon successful completion of the course, students will be able to explain two basic ideas: (i) applying control methods for learning; (ii) applying learning methods for control. Students will be able to understand the mathematics underlying such interdisciplinary research. Students will be prepared to tailor their own expertise (in either control or machine learning) for research at the intersection of control and machine learning.

Outline of Topics:

- A Control Perspective on Optimization Methods and Network Structures in Large-Scale Machine Learning (12 hours):
    - Brief introduction to empirical risk minimization and related optimization Methods
    - Dynamical system perspectives for optimization methods
    - A unified analysis of large-scale optimization methods via dissipativity
    - Jump system theory for stochastic optimization
    - Lure-Postnikov type Lyapunov functions
    - Weighted off-by-one integral quadratic constraint
    - Quadratic constraints for designing certifiably robust neural networks
    - Multiplier theory and KYP lemma

- Control-Oriented Analysis Tools for Reinforcement Learning Algorithms (6 hours):
    - Analysis of temporal difference learning with linear function approximators
    - Analysis of Q-learning with linear function approximators
    - Analysis of emphatic TD learning
    - Variance reduction techniques in TD learning

- Reinforcement learning for linear quadratic control (12 hours):
    - Brief review of linear quadratic regulator (LQR)
    - Policy gradient for LQR: REINFORCE and Evolutionary Strategies (ES)
    - Convergence guarantees of policy gradient on LQR problem
    - Q-learning and approximate policy iteration for LQR
    - Iterative feedback tuning for gradient estimation
    - Policy gradient for linear quadratic control of large-scale switching systems
    - Policy gradient for linear quadratic Gaussian (LQG) with partial observation
    - Iterative learning control
    - Sample-based model predictive control

- Robustness and safety in learning-based control (12 hours):
    - Model-based robust control: H-infinity control
    - Risk-sensitive control: linear exponential quadratic Gaussian (LEQG)
    - Policy gradient for mixed H2/H-infinity control and LEQG (global convergence and implicit bias)

- Goldstein’s subgradient method for H-infinity control
- Adversarial robust reinforcement learning and linear quadratic games
- Zeroth-order optimization for robust control
- Robustness in imitation learning
- Regularization of model-free deep reinforcement learning via prior model-based control design
- Safe control via control barrier functions

Text: none required; instructor’s lecture notes and slides will be used.

Coursework: 60% regular homework sets; 40% written research report

Prerequisites: ECE 515. ECE 534 and ECE 490 are recommended, but not required.