ME599-004: Data-Driven Methods for Control Systems
University of Michigan – Winter 2024

Registration
(3 units) Graduate level. A background in classical controls, linear algebra and state-space modeling is strongly recommended.

Lectures
Tuesdays and Thursdays 12:00-13:30 ET, 01/10/2024 – 4/23/2024, GGBL 2147

Course Description
Data is vital in control systems. At bottom, data acquisition is essential for feedback in closed-loop systems. But more interestingly, input and output system data, stored over time, can be used to find suitable control signals, or finetune control signals. The focus of this course is to discuss strategies for utilizing system data in these ways. The course will begin with a review of control systems fundamentals including classical, optimal and nonlinear control design. The course will then discuss prominent methods that learn control signals directly with or without a model, namely, reinforcement learning and iterative learning control. This will be followed by indirect methods that learn models for controls including classical system identification, machine learning, and deep learning approaches for dynamical systems. We will conclude by exploring emerging trends such as physics-informed neural networks for controls. Examples that illustrate how to choose an appropriate learning strategy for a given problem will be drawn from various control applications.

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Office Hours
Tuesdays 15:00-16:00 ET and Fridays 13:00-14:00 ET, GGBL 3468

Programming
This course will entail a decent amount of programming in MATLAB and/or Python.

Website (Canvas): https://umich.instructure.com/courses/666164

References (Optional)

1. Brunton and Kutz, *Data-Driven Science and Engineering: Machine Learning, Dynamical Systems, and Control*, 2nd ed., Cambridge University Press, 2023
2. Ljung, *System Identification: Theory for the User*, 2nd ed.,Prentice Hall, 1999
3. Keesman, *System Identification: An Introduction*, Springer, 2011

Assessment
Homework Problems – 80%
(Group) Project/Study – 20%
Quizzes/additional homework problems (optional) – 5% (Bonus points)

Eight (8) homework problem sets will be issued during the semester. At least one (1) week will be given for completing each. Certain homework problems would have multiple approaches for solving them. A critical leaning outcome of this course is to discern what approach, of potential alternatives, is suitable for a given problem. Hence your solutions should highlight your thought process and outline assumptions you make and why those assumptions are reasonable.

There is no midterm or final exam. Instead, a final project/study will be required. The final project will include an initial project proposal, and final deliverables in the form of a written report and short presentation. Portions of the final deliverables will be peer-reviewed (by other students in this class) and the instructor will assign a final score. The final project is intended as an opportunity for you to exercise the knowledge gained from this course and explore topics that may be beneficial to your graduate research. It is also intended to encourage working with fellow students as a group. Hence, you are expected to work in teams of 2 or 3, or receive the instructor's permission to work by yourself on the project.

If time permits, there will be a few in-class quizzes (that are entirely optional); otherwise, optional homework problems would be included in the homework sets for additional (5 bonus) points.

Content

1. Data Analysis & Machine Learning Preliminaries

- Fourier Transforms & Applications, Dimensionality Reduction
- Regression Analysis: Least Squares, Nonlinear regression
- Review of unconstrained optimization
- Classification: Discriminants, Support Vector Machine, Clustering, Neural Networks

2. Dynamical Systems & Control (P)review

- ODE's, Transfer functions, State Space representations
- Classical and linear controls theories: PID, frequency-domain analysis, state feedback & estimation, Linear Quadratic Regulator (LQR), Model Predictive Control (MPC)
- Nonlinear control

3. Learning Control

- Iterative Learning Control
- Reinforcement Learning (RL)

4. Learning Models for Controls

- Classical System Identification (ID) and Controls: Frequency & impulse responses, autoregressive models with exogenous input (ARX), Nonlinear system ID and adaptive control
- Koopman Operator, Dynamic Mode Decomposition (DMD), Sparse Identification of Nonlinear Dynamics (SINDy)

5. Deep Learning for Controls & Recent Topics

- Multilayer NN, Recurrent NNs, Convolutional NN, Autoencoders, Generative Adversarial Networks; Physics-Informed Deep Learning

The objective of this course is to *introduce* approaches for controlling systems using data. Hence, we do not treat the topics exhaustively as they each constitute subjects of entire courses in their own right. Please note that this outline is subject to modifications as is deemed suitable for the class.

Collaboration Policy and Honor Code

You are allowed, and indeed encouraged, to consult with other students and faculty. You may work in groups if desired. However, every student, separately and individually. must conduct all elements of a submission. This includes creating. editing, and submitting your own report. code, and calculations. Using a template or any partially created elements from another student is not allowed. Suspected violations of this homework policy may be reported to the College of Engineering's Honor Council. Information about the Honor Council can be found at https://elc.engin.umich.edu/honor-council/.

Policy on Generative AI

Learning how to use AI tools such as ChatGPT is important for all of us. Used properly, ChatGPT can enhance our work; used improperly, it can border on plagiarism. If you have used ChatGPT on anything you submit for this class, please include an appendix containing (1) your key conversations/usage of the chatbot, including your original prompts and its responses; (2) a summary of what you learned from the experience using the chatbot (e.g., how did it help you. did it provide incorrect data, etc.); and (3) description of how you reworked and revised the content so that your final submission was both *factually accurate* and *reflected your own writing*. If you used ChatGPT to help work on your code, you must fully *understand* the code in its entirety and be able to recreate it when requested. Otherwise, treat the AI tool as a classmate. As such, copying text directly from the AI tool is not permitted.

Accommodation for Students with Disabilities

If you think you need an accommodation for disability, please contact Services for Students with Disabilities (https://ssd.umich.edu/; 734-763-3000 or ssdoffice@umich.edu). For students who are connected with SSD, accommodation requests can be made in "Accommodate". If you have any questions or concerns, please contact your SSD Coordinator or visit SSD's Current Student webpage. SSD considers aspects of the course design, course learning objects and the individual academic and course barriers experienced by the student. Further conversation with SSD, instructors, and the student may be warranted to ensure an accessible course experience.