Lahore University of Management Sciences
EE 5614/MATH 549– Learning for Dynamics & Control
Spring 2023

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Course URL (if any)	

Course Basics

Credit Hours	3			
Lecture(s)	Nbr of Lec(s) Per Week	2	Duration	1hr-15min each
Labs (per week)	Nbr of Lec(s) Per Week	0	Duration	
Recitation (per week)	Nbr of Lec(s) Per Week	1	Duration	60 minutes

Course Distribution

Core	
Elective	BS, MS, PhD in Electrical Engineering
Open for Student Category	EE (Seniors), EE (Grad), all SSE majors
Close for Student Category	Anyone not meeting prerequisites

COURSE DESCRIPTION

Data-driven discovery is increasingly becoming important for modeling, predicting, and controlling complex systems that evolve in time and space. Such approaches are being applied to climate, neuroscience, epidemiology, robotics, fluids, chemical process control, agriculture, and many other areas. In this course, students will learn some of the popular approaches towards discovering low-dimensional patterns in high-dimensional data (e.g. by using SVD), coordinate transformations that simplify dynamical models (e.g. by Dynamic Mode Decomposition), methods for fusing measurement data with analytical models (e.g. by Kalman Filtering), taming instabilities and disturbances by optimal feedback control (e.g. using LQG) and designing sensor networks for monitoring complex environments (e.g. via Gaussian Processes based Kernel observers). The course should appeal to students from a variety of disciplines in science and engineering, especially those who wish to apply techniques from machine learning and data sciences to scientific investigations and engineering design.

COURSE PREREQUISITE(S)

EE-561.Digital Control Systems OR EE-514 / CS 535 Machine Learning

The course requires mathematical maturity (linear algebra, differential equations, probability) and the ability to program fluently (MATLAB or Python)

Grading Breakup and Policy

Homeworks (4 x 3%) = 12%
Mini-Projects (4 x 6%) : 24%
Midterm Examination: 25%
Final Examination: 30 %
Presentation: 4%
Class Participation: 5%

Examination Detail

Midterm Exams	Duration: 1.5 hrs Exam Specifications: Open book, open notes, and calculators allowed
Final Exam	Duration: 3 hrs Exam Specifications: Open book, open notes, and calculators allowed

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Course Learning Outcomes	
EE562- CLO1: CLO2: CLO3:	 Perform dimensionality reduction to simplify complex dynamical systems Observe and control complex phenomenon by data-driven discovery Implement algorithms to simplify, learn and control complex dynamics

Relation to EE Program Outcomes

	Related PLOs	Levels of Learning	Teaching Methods	CLO Attainment checked in
CLO1	PLO2-Problem Analysis	Cog-5	Instruction, Tutorial, Assignments	Midterm, Quizes
CLO2	PLO1-Engineering Knowledge	Cog-5	Instruction, Tutorial, Assignments	Midterm, Final
CLO3	PLO5-Modern Tools	Cog-5	Instruction, Tutorial, Assignments	Homeworks, Final

COURSE OVERVIEW

Week	Modules	Topics	Applications and Examples	Milestones
1-2	**Introduction**	**Lectures (4):** Overview; review of linear dynamical systems; **Tutorials (2)**: Linear algebra review		**HW-1**
3-4	**Singular Value Decomposition**	**Lectures (3)**: Matrix approximation; Least squares; PCA; Tensor decompositions **Tutorial (1)**: MATLAB/Python tools and tricks for fast linear algebra	**Application**: reconstruction of remote sensing imagery	**Mini-project 1**: Reconstruct images from spectral measurements (Datasets to be provided)
4-5	**Dynamic Mode Decomposition**	**Lectures (3)**: Nonlinear complex dynamical systems; DMD algorithm; sparse identification of dynamical systems; **Tutorial (1)**: Using Python/MATLAB to simulate dynamical systems	**Application**: weather models, fluid dynamics	**HW2**
6-7	**Linear Control Systems**	**Lectures (4)**: Linearization; Closed-loop linear control systems; controllability; observability; LQR; reduced order linear models; **Tutorials (1)**: LTI systems review for non-EE majors	**Applications**: Mechanical systems; robotics	**Mini-project 2**: Forecast Lorenz Chaotic Model (Solvers to be provided)
8-9	**Kalman Filtering**	**Lectures (4)**: Optimal linear estimation; Kalman filtering; LQG **Tutorials (1)**: Review of probability and random processes	**Applications**: Air traffic control	**HW3**
	Midterm			
10-11	**Dimensionality Reduction and System Identification**	**Lectures (4)**: PCA-based balanced realizations for feedback control; system identification of linear parameter models;	**Applications**: chemical process control; communication systems	**Mini-project 3**: Kalman Filter radar returns for discovering aircraft trajectories

		Tutorials (2): Using the MATLAB control systems and system identification toolboxes		(Datasets and Models to be provided)
12-13	**Koopman Operator Theory**	**Lectures (3)**: Koopman theory-based embeddings; data-driven discovery of dynamics; Koopman theory of neural networks; **Tutorials (1)**: Working in infinite-dimensional vector spaces	**Application**: Environmental monitoring; fluid mechanics;	**HW4**
13-15	**Evolving Gaussian Processes**	**Lectures (4):** Gaussian Processes based regression; Kernel observers; Kernel controllers; **Tutorials (1)**: Using the MATLAB/Python GP Toolboxes	**Application**: Environmental monitoring; fluid mechanics; agriculture	**Mini-project 4**: Discover and control anomalies in agricultural field data (Datasets to be provided)
15	1 Session **Student Presentations**	Project presentations		

Textbook(s)/Supplementary Readings

Primary text

- Brunton, Steven L., and J. Nathan Kutz. *Data-driven science and engineering: Machine learning, dynamical systems, and control*. Cambridge University Press, 2022.

Papers, handouts, secondary texts

Dynamic Mode Decomposition theory

- Proctor, J.L., Brunton, S.L. and Kutz, J.N., 2016. Dynamic mode decomposition with control. *SIAM Journal on Applied Dynamical Systems*, *15*(1), pp.142-161.
- Kutz, J.N., Brunton, S.L., Brunton, B.W. and Proctor, J.L., 2016. *Dynamic mode decomposition: data-driven modeling of complex systems*. Society for Industrial and Applied Mathematics.

Koopman theory

- Brunton, S.L., Budišić, M., Kaiser, E. and Kutz, J.N., 2022. Modern Koopman theory for dynamical systems. SIAM Review, Vol 64, Issue 2.
- Dogra, A.S. and Redman, W., 2020. Optimizing neural networks via Koopman operator theory. *Advances in Neural Information Processing Systems*, *33*, pp.2087-2097.

Evolving Gaussian Processes

- Whitman, J.E., 2018. Modeling and inference of the dynamics of spatiotemporally evolving systems using evolving gaussian processes.
- Whitman, J.E., Maske, H., Kingravi, H.A. and Chowdhary, G., 2021. Evolving gaussian processes and kernel observers for learning and control in spatiotemporally varying domains: With applications in agriculture, weather monitoring, and fluid dynamics. *IEEE Control Systems Magazine*, *41*(1), pp.30-69.
- Liu, M., Chowdhary, G., Da Silva, B.C., Liu, S.Y. and How, J.P., 2018. Gaussian processes for learning and control: A tutorial with examples. *IEEE Control Systems Magazine*, *38*(5), pp.53-86.
- Kingravi, H.A., Maske, H.R. and Chowdhary, G., 2016. Kernel observers: Systems-theoretic modeling and inference of spatiotemporally evolving processes. *Advances in neural information processing systems*, *29*.

Prepared by:	**Abubakr Muhammad, Oct 13, 2022**