APMTH 232/ES 202: Learning, Estimation and Control of Dynamical System
Spring 2024

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Office hours: Monday 11am-12pm pm (SEC 3.307) and by appointment

Location: SEC 2.118
Meeting Time: M/W: 09:45 AM - 11:00 AM
Teaching fellows: Runyu Zhang

Office hours: Lina's office hours: Mon, 11am-12pm, SEC 3.307.

And by appointment

Prerequisites: Linear algebra, Differential equations, Systems and Control, Probabilities (AM 120, ES 155, ES 150 or equivalent). Undergraduates need permission.

ES 155 materials are available at: https://www.dropbox.com/sh/z6z15x78lmdndbm/AABKiy_U6OxJMVua7O8w06nda?dl=0
If you haven't taken ES 155, please make yourself familiar with it (Lecture 1-17) within the first couple of weeks. Otherwise, it might be better for you to take ES 155 first. I won't repeat the materials that were covered in ES 155. This class almost purely focuses on the mathematics behind control. Because a semester is short, I have to choose the focus. If you're more interested in applications, you need to count on yourself to find the connections with real-world applications. But I am happy to discuss the application and your search outside of classroom.

If you feel the first Pset is extremely difficult for you, the class might not good for you.

Course Description:
This graduate level course studies dynamic systems in time domain with inputs and outputs. Students will learn how to design estimator and controller for a system to ensure desirable properties (e.g., stability, performance, robustness) of the dynamical system. In particular, the course will focus on systems that can be modeled by linear ordinary differential equations (ODEs) and that satisfy time-invariance conditions. The course will introduce the fundamental mathematics of linear spaces, linear operator theory, and then proceeds with the analysis of the response of linear time-variant systems. Advanced topics such as optimal control, robust control, model predictive control, system identification and reinforcement learning (for unknown dynamical models) will be presented based on allowable time and interest from the class. The material learned in this course will form a valuable foundation for further work in systems, control, estimation, identification, reinforcement learning, detection, communications and robotics.

Note: Though we have ``learning'' in the course title, after careful consideration, the course will first make sure that we cover the foundations of dynamical systems and control well before we move to any trending topics of learning or reinforcement learning. If your goal is mostly to learn reinforcement *learning, this is not a right class for you because it is hard to predict how much time we have for learning.*

(Tentative) Topics include:

First part: the first half of the semester (Lecture-based)

- A review of linear algebra and matrix theory. Least-squares approximation, singular value decomposition and matrix norm.
- (Linear) ordinary differential equations: existence and uniqueness of solutions, Lyapunov Stability, the state-transition matrix and matrix exponential.
- Input-output and internal (Lyapunov) stability.
- Controllability and State Feedback.
- Observability and output Feedback.
- System Norms

Second part: the second half of the semester (mixed with Lectures and student presentations for research papers)

- Advanced topics such as optimal control and dynamical programming, system identification, robust control, model predictive control, adaptive control, and reinforcement learning will be presented based on allowable time and interest from the class.

Notes:

First class will meet on Monday, Jan 22th;

Students are only allowed to take either Eng-Sci 202 or APMTH 232 for credit. There are no differences in the grading policy for the two courses.

Lectures

Course lectures are on Monday and Wednesday 9:45am to 11:00am at ***.

Lecture notes and course materials will be available on the course website after each lecture.

References:

- J. P. Hespanha, Linear Systems Theory, Princeton University Press, 2009 (***Primary for the first half of the class***)
- Lecture note of MIT Open Course, 6.241, Dynamic Systems & Control, https://ocw.mit.edu/courses/electrical-engineering-and-computer-science/6-241j-dynamic-systems-and-control-spring-2011/readings/
- Luenberger, David G. *Introduction to dynamic systems; theory, models, and applications*. John Wiley & Sons, New York, 1979.
- C.T. Chen, Linear Systems Theory and Design. Oxford University Press, 3rd Edition, 1999.
- Wilson J. Rugh, Linear System Theory, 2nd Edition, Prentice Hall, 1996
- G. Dullerud, F. Paganini, A Course in Robust Control Theory, Springer, 2000.
- J. Doyle, B. Francis, A. Tannenbaum, Feedback Control Theory, Dover Publication, 2009.
- G. Strang, Linear Algebra and its Applications 3rd edition, 1988 (Linear Algebra Reference).
- System identification

- Sutton, Richard S., and Andrew G. Barto. *Introduction to reinforcement learning*.2nd Edition. Cambridge: MIT press, 2018.
- Bertsekas, Dimitri P., et al. *Dynamic programming and optimal control*. 4th edition. Belmont, MA: Athena scientific, 2017. (Other editions are good too)
- Bertsekas, Dimitri P., and John N. Tsitsiklis. *Neuro-dynamic programming*. Athena Scientific, 1996.

Grading

First of all, I would like to highlight that this is a graduate level course. I hope you focus on learning the content rather than the grades. No matter whether you are a PhD student, master student, or undergraduate student, I would treat you as a highly-motivated PhD student!

The final grade will be based on course participation, homework sets, a midterm exam and a final project.

- *Homework (35%):* The plan is to have regular Psets for the first part of the class (we estimated that these regular Psets won't be more than 5 times). For the second part, we will design some assignments to guide you to read papers.

  Late homework within 2 days of the due date is acceptable but the grades of the late homework will be 25% discounted. *No late homework after 2 days will be accepted* without a note from the health center or the student's Resident Dean.

  Please write down the number of hours you spent on the homework at the right-upper corner of each assignment.

- *Course Participation* (10%): Students are encouraged to ask questions, participate in the discussions, and provide feedbacks. This also includes your participation in class for the second half of the class when your peers are giving presentations.

- *Presenting and leading class discussions*; reflection notes (25%): See guidelines at the end, "**Guidelines for the second half of the class (starting from the class on March 27)".**

- *Final project (30%):* The final project should be done in teams (2-3 team members). If you want to do the project solely, you should discuss it with the instructor and provide a strong reason**. Though the course materials will be highly mathematical (proof-based), the project can be applied.**

  Students are encouraged to build off the material that is presented in class and that is related to their own research. Another example is that each team/student picks one (advanced) topic to review. This will require students to review papers or advanced textbooks. The end results should incorporate a report and a presentation.

  Before the Spring break, each team must submit a short proposal (no more than 1 page) about the final project topics. By April 10th, students should submit a progress report (around 4 pages).

  Students are welcome to discuss the topics with the instructor or ask for suggestions.

  The project final report should be written in IEEE transaction format (https://journals.ieeeauthorcenter.ieee.org/create-your-ieee-journal-article/authoring-tools-and-templates/ieee-article-templates/templates-for-transactions/) or in SIAM journal format (https://www.siam.org/publications/journals/about-siam-journals/information-for-authors#dnn_ctr2112_ContentPane). You will find it will be easier to do everything in Latex.

Collaboration Policy

Collaboration on homework assignments is encouraged. You may consult outside reference materials, other students, the TA, or the instructor, but you cannot consult homework solutions from online or prior years, and you must cite any use of material from outside references. All solutions that are handed in should be written up individually and should reflect your own understanding of the subject matter at the time of writing.

No collaboration is allowed on the midterm exams.

Course website:
We will use the course website of AM 232 (https://canvas.harvard.edu/courses/70107) for both APMTH 232 and Eng-Sci 202. Please let me know if you have problem of accessing the website. Updates will be made daily as appropriate. It is essential that you check the website periodically. Posted will be lecture notes, problem set assignments, course announcements, changes in course materials, and answers to pertinent questions.

ED discussion:
We will use ED discussion for Q&A.

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Guidelines for the second half of the class

Reflection notes (from everyone): You are required to read papers and other listed reading materials before each class. (Main readings and extra readings will be made very clear under each reading assignment on Canvas. Extra Readings are optional. They are also posted in the course schedule table on the homepage of the course canvas. We will use Perusall as an online forum to read papers together.) Finishing reading the papers in detail is indeed a very challenging task. You just need to do your best according to your background and time constraint.

You MUST submit comments (reflect note) on the readings by midnight(11:59) before class once we start to read papers. The reflection note should be submitted on Canvas under the corresponding reading assignment. Each reflection note should be no more than 1.5-page PDF (11 font size; 1 inch margin; Single column; Letter size). ¾-1 page is a good amount.

You also need to at least provides 5 comments directly on the papers on Perusall (It can be questions, comments, or your comments to other students' comments). Perusall has built-in function to track students' activities.

Your comments should include good-faith answers to posted reading questions (if any) and general comments. For research papers, things to think about for general comments include (you don't need to hit all of these...):

- what is the main contribution of the paper?
- is this important, why?
- what was the main insight in getting the result?
- is there an interesting related paper/resource that you found?
- what is the most interesting result to you and why?

- what is not clear to you?
- what did the authors not do?
- what are the most important assumptions, are they limiting?
- what applications does this suggest?
- how does this relate to other things we have seen?
- what extensions does this suggest?
- can you suggest a two-sentence project idea based around the ideas in this paper?
- are there anything from this paper that will help your research?

I also recommend you read the blog post by Prof. Michael Mitzenmacher on How to Read a Research Paper.

You won't be graded on the correctness or the rigorousness of your answers to reading questions. These questions are designed to assist in understanding the material and to encourage discussion.

Discussion leaders/presenters. Each team will present papers for one class and lead a class discussion. You are required to talk to Lina at least one week before your presentation about your plans for the presentation and any questions or concerns relating to the presentation. Try to schedule the zoom meeting time with Lina as early as possible. Lina's zoom account is nali@seas.harvard.edu; You can add Lina into your zoom contact and message her on zoom which might be more convenient.

Your goal as a discussion leader/presenter is to pick out highlights of the text(s), lead us through some interesting/relevant/difficult derivations or concepts, and/or highlight some interesting questions for discussion. Please refer to the examples of questions listed above.

Students are also asked to propose reading questions for the papers they present. Presentation Notes from COMPSCI 236R provide a good guideline for presentation. So please refer to that note for expectations on student presentations.