AA/EE/ME 548: Linear Multivariable Control

Lecture 01

3/31/2025

Course logistics

Expectations

#1 principle: Respect each other's time

- Be an active participant
- Communicate early
- Engage with peers

- **Teaching team**:
  - *Instructor*: Professor Karen Leung,
  - *TA*: Oliver Sheridan
  - For private matters, please use: `aa548-spr25-staff@uw.edu`
  - Ed Discussion: Use to ask questions useful to the class / not personal
    - Extra credit for active participation
    - Primarily student-driven discussion / teaching staff lightly monitoring it
  - Course announcements via Canvas Announcements
- **Office hours**: Karen (TBD), TA (TBD)
- **Programming language**: Python
- **Textbook**: Use lecture notes + recommended text (see syllabus)
- **Recording**: We will try our best, but no promises. In-person attendance is strongly encouraged.

New this year

- Course material will be available online
  - Syllabus
  - Homework
  - Project information
  - Lecture material*
- Will be updated as we progress through the quarter
  - Course notes are not a replacement for attending lectures!
  - No guarantees on timeliness with lectures. You are still expected to attend lectures.
- ***Preliminary notes***
  - Welcome feedback
    - Typos, improvements, errors
    - Email aa548-spr25-staff@uw.edu, submit a pull request, post an issue
    - Can earn extra credit

https://uw-ctrl.github.io/lmc-book/

Homework (30% of grade)

- 3 homework sets
  - Homework 1: Focus on coding basics and fundamentals
  - Homework 2: The “fun stuff”
  - Homework 3: A bit shorter to help you focus on your course project + project progress update
- Mixture of theory and coding
  - We will not debug your code, but can help with conceptual questions
- Submit Jupyter notebook and PDF on Canvas
  - Notebook will consist of written (markdown/LaTex) and Python coding
- Collaboration and having study groups is highly encouraged. But your write-up must be your own. Copying whole or parts of code from others or GenAI is considered a violation of the student conduct code.
  - Please post on EdDiscussion to find study buddies

Homework (30% of grade)

- No late submissions!
  - Part of your grade comes from self-grading
- Full grade is awarded for on-time submission
  - With a reasonable attempt at the homework
    - E.g., blank submission is not earn you any credit.

Homework self-grading (15%)

- Once homework solutions are released, you will grade your own homework.
- 1 week turn-around time
- Submit a write-up summarizing your homework performance. Things like:
  - Where you were correct
  - Where your answer differed from solution but you believe is equally correct
  - Where you were incorrect but can explain why the error was made
  - What you didn't realize previously, but now know after reviewing the homework solutions
- Full grade is awarded for on-time submission and a reasonable attempt at the write-up
- (New this year)

Homework solution / example write-up (10%)

- You will sign-up for one of the following options
  - Homework problem solution write-up
  - Worked example on a topic covered/mentioned in the course
- Need to do one of them once during the quarter
- 1 week turnaround
- Homework solutions
  - TA will share the students' homework (anonymized!)
  - You will provide a detailed solution to a problem
  - Provide a summary of any common mistakes
- Worked example
  - Sign up for a particular week
  - Pick a topic covered/mentioned during lectures and create an illustrative worked example for that topic
    - Use a Jupyter notebook with text and code and interactive elements
  - Include in course notes (with your permission and proper acknowledgement)
- Sign-up sheet will be posted on Canvas
- Submit on Canvas
- TA will consolidate submitted solutions, and release them for your peer-grading assignment.
- (New this year)

Course project (45% of grade)

- Individual, or group of 2-3 students
- A deeper exploration into topics studied in this course and apply it to an interesting system or application, or it could be taking topics covered in this course and connecting them with your existing research.
- Project proposal (5%), lightning talk (5%), poster (15%), report/website (15%), peer review (5%)
  - More instructions to follow
- Lightning talk and poster session in week 10
- Report due during finals week
- AA SHARC week is an opportunity to see what a poster session is like (May 20th)
- More info released later

Extra credit (5%)

- Active participation in EdDiscussion
  - Answering questions
  - Asking insightful questions
    - Example of non-insightful question: “I don’t understand X, can someone explain it to me?”
    - Suggesting references or papers that may be of interest to the class.
  - Bringing up typos/points of confusion in the homework, and helping provide clarification.
- Feedback/suggestions on course notes

Assumed knowledge

- AA/EE/ME 547 or equivalent
  - Fundamental feedback control concepts (feedback, stability, etc)
  - Very comfortable with linear algebra and multivariable calculus
- Python programming
  - Many popular and powerful packages are supported in Python
  - If you don't know it, you should learn it.
    - For any job in controls (research or industry) you will spend most of your time on the computer
      - Running/reviewing other people's code
      - Writing your own code
      - Collecting data and processing/visualizing it
  - You will read up on the documentation on how to use packages/functions

Communication

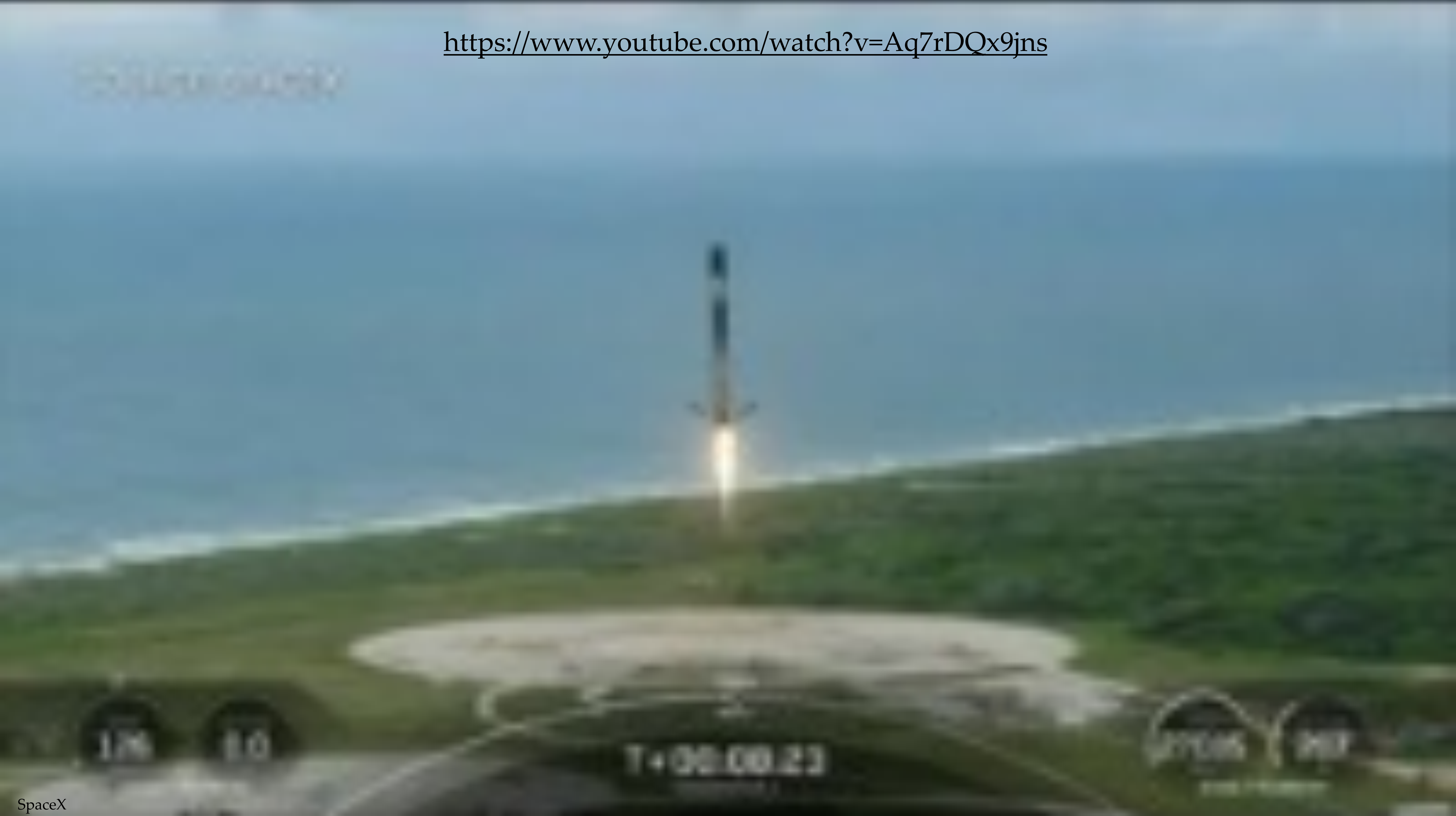
- Regarding personal administrative items: send email to
  - `aa548-spr25-staff@uw.edu`
- Teaching staff making announcements to the class
  - Canvas announcements.
- Discussion about course materials and logistics
  - Ed Discussion board
  - Encourage peer-to-peer discussion
  - Teaching staff will lightly monitor board but will answer general questions about logistics

What is this course about…

https://www.youtube.com/watch?v=joIsgP9StAY

Subosits, J. and Gerdes, J.C. , *From the Racetrack to the Road: Real-Time Trajectory Replanning for Autonomous Driving*, IEEE Transactions on Intelligent Vehicles, vol. 4, no. 2, 2019

https://www.youtube.com/watch?v=EGABAx52GKI https://www.youtube.com/watch?v=Aq7rDQx9jns



SpaceX

What is the secre

MODEL-PREDICTIVE CONTROL

Having identified the boxes, ramps, or barriers in front of the robot and planned a sequence of maneuvers to get over them, the remaining challenge is filling in all of the details needed for the robot to reliably carry out the plan.

Atlas' controller is what's known as a *model-predictive controller* (MPC) because ... to

Exploiting knowledge about the dynamics and applying optimization-based control

VI. L

To transform ... quickly, the dyn... tory. While not required to produce a useful modified the nearer this nominal trajectory is to being feasible optimal the better since less approximation error wi introduced by the linearization. The method of discre chosen to limit the resulting error as much as possib

A. *Linearization*

To include the vehicle dynamics as equality cons quadratic program (QP), we place the equations of mo following linear form:

$$x(s)' = A(s)x(s) + B(s)u(s),$$

where $x(s) = [\Delta t \; e \; \Delta V \; \sigma]^T$, $u(s) = [\Delta a_x \; \Delta da_y]^T$ notes a perturbation from the nominal value at that p

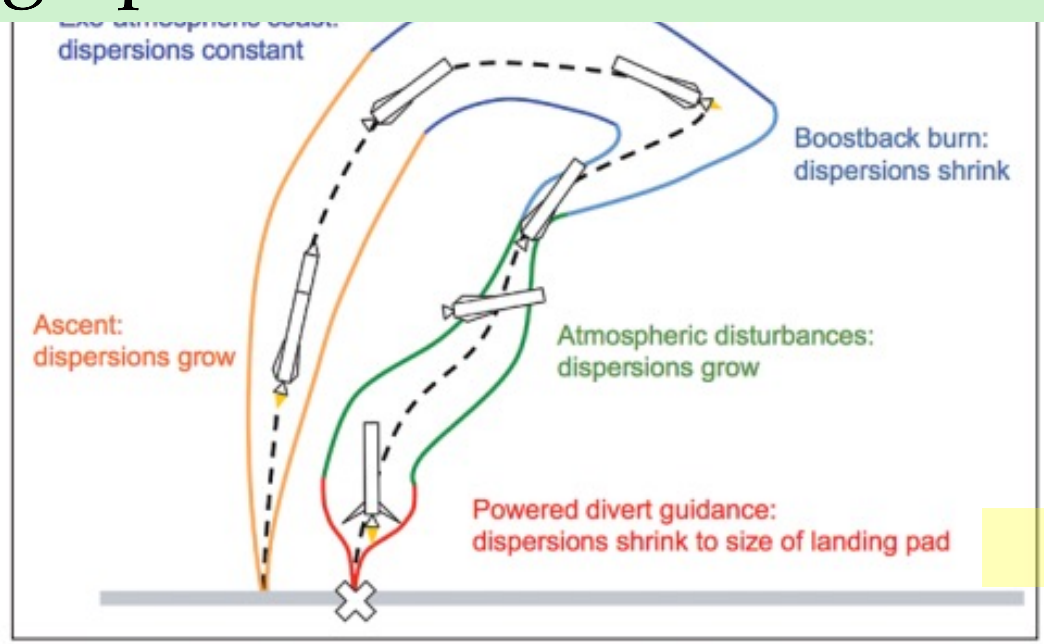


FIGURE 4 Phases of an F9R return-to-launch-site mission. The colored lines represent the largest possible variations in the trajectory, known as dispersions.

... 2007; ...0).

Because Earth's atmosphere is 100 times as dense as that of Mars, aerodynamic forces become the primary concern rather than a disturbance so small that it can be neglected in the trajectory planning phase. As a result, Earth landing is a very different problem, but SpaceX and Blue Origin have shown that this too can be solved. SpaceX uses CVXGEN (Mattingley and Boyd 2012) to generate customized flight code, which enables very high-speed onboard convex optimization.

Subosits, J. and Gerdes, J.C. , *From the Racetrack to the Road: Real-Time Trajectory Replanning for Autonomous Driving*, IEEE Transactions on Intelligent Vehicles, vol. 4, no. 2, 2019
Boston Dynamics, Atlas, https://www.bostondynamics.com/resources/blog/flipping-script-atlas
SpaceX: https://nap.nationalacademies.org/read/23659/chapter/10

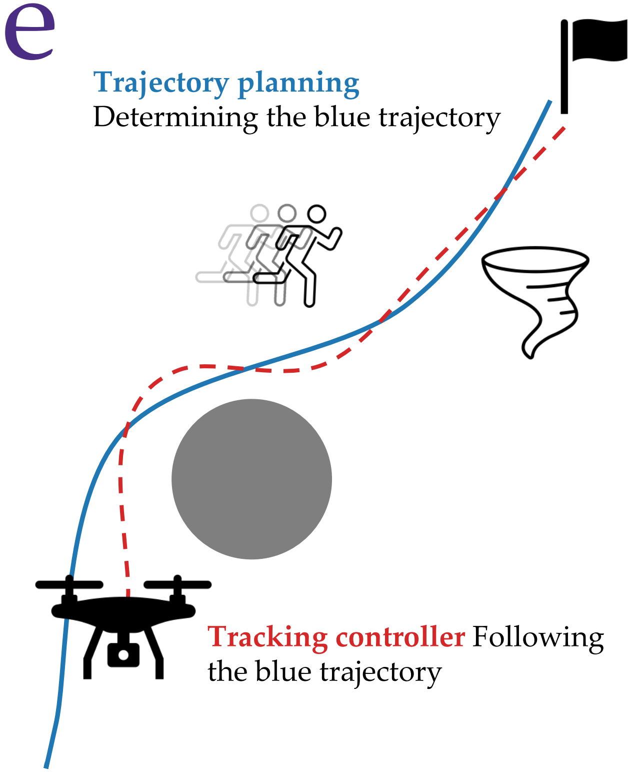
Closed-loop control for real-world systems is hard…

- In this course…
  - Explore how we design controllers by approximating real-world (i.e., nonlinear) systems as *linear* systems
  - Cover a number of control design techniques & show that they are tractable for linear systems
  - Focus on *optimization-based* control (very powerful thanks to modern computing)

- Emphasis on theory (intuition) and implementation

Scope of this course

- A model-based approach to control synthesis
  - Assume we have a reasonably good model of the system
- What you can after taking this class
  - Frame a control problem as an optimization problem
  - Construct tracking controllers, i.e., system to follow a nominal trajectory
  - Synthesize a trajectory given goals and constraints, i.e., go from point A towards point B while avoiding things + additional constraints (computing the nominal trajectory)
- What this course is **not** about
  - Model-free approaches (no model), i.e., reinforcement learning or deep learning
    - But can used learned components for some parts
  - Optimization theory
    - We will cover some basics, but we will not go into depth
  - State-estimation/filtering course
  - Programming class
- Topics lightly touched but beyond the scope of this course
  - Stochastic control, robust control, nonlinear control, adaptive control, state estimation, reinforcement learning



Potential applications
- Human-robot interactions
- Spacecraft landing/docking
- Aircraft landing/flying
- Delivery robots
- Autonomous driving

This week's plan

Week-by-week schedule

Note: *Italicized* text indicates planned topics, but subject to change.

Date	Week	Topic	Milestones	Links
March 31 April 2	1	*Introduction, state-space dynamics, linearization, continuous and discrete time dynamics, intro to optimization*	hw 1 out	
April 7 April 9	2	*Control Lyapunov Functions, control invariant sets, Control barrier functions, CLF-CBF-QP*		
April 14 April 16	3	*Guest lecture(?), introduction to sequential decision-making*		
April 21 April 23	4	*Value iteration, HJB equation, HJ reachability*	hw 1 due; hw 2 out	

- TA OH this week on help with setting up Python environment

"basic skills"

Extending Lyapunov theory to control synthesis

Control synthesis + reasoning over a future horizon