MEE5114 Advanced Control for Robotics (Spring 2022)

Course Introduction

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Southern University of Science and Technology

Course Information:

- **Title: Advanced Control for Robotics (English)**
- **Time:** Monday 2:00- 3:50pm / Wednesday 10:20-12:10 am (odd week)
- **Location:** 荔园 2栋 202 / 一教 506
- **Webpage:** Blackboard &

  https://www.wzhanglab.site/teaching/mee-5114-advanced-control-for-robotics/

- **Instructor:** Wei Zhang, zhangw3@sustc.edu.cn
- TA: Zhen Fu, Yangxing Shang, and Ben Liu

Make sure you are in the Wechat group and can log in the Blackboard system

What is this course about?

- Develop a solid foundation in robot modeling and control to conduct cutting edge research in robotics
  - **Math:** linear algebra, optimization
  - **Modeling**: Advanced rigid body kinematics and dynamics (screw theory and spatial vectors)
  - **Optimization**: learn how to formulate robotic decision and control problem as tractable optimization problems

    Lyapunov func. control Lyapunov func
  - **Control**: Nonlinear control, optimal control, Model predictive control
- This is a **THEORY** class rather than a technology/engineering class.
  - Serves as math requirement

    TR-O IJRR. ICRA IROS
  - This year: no final project, we will have a final take-home exam
  - Homework and project assignment are crucial
  - Some programming will be involved, but only for better appreciation of the theory covered in class.
- **Target Students:**
  - PhD students in robotics with a strong need of advanced control theory
  - Master students in control and robotics with a strong desire to pursue PhD degree
  - Students who can devote **substantial time** to read and learn outside classroom

Tentative Schedule:

1. **Continuous time linear systems and Matrix Exponential (1 Week)**
2. **Advanced Kinematics and Dynamics: (4 Weeks)**
   a) Rigid body configuration and velocity
   b) Exponential coordinate of rigid body motion
   c) Kinematics of open chain
   d) Rigid body dynamics
   e) Multibody dynamics (Recursive Newton-Euler Algorithm, inverse and forward dynamics)
3. **Basic Optimization (2 Weeks)**
   a) Optimization problems and basic duality theory
   b) Semi-definite Programming (SDP) and linear matrix inequalities
4. **Nonlinear Stability and Stabilization (3 Weeks)**
   a) Lyapunov stability theory
   b) Numerical construction of Lyapunov functions via semi-definite programming
   c) Control-Lyapunov Function for stabilization
5. **Basic Robot Control: (2 Weeks)**
   a) Differential IK
   b) Robot Motion Control (Computed Torque Method, Task-space Inverse Dynamics (TSID))
6. **Optimal Control and Model Predictive Control (4 Weeks)**
   a) Optimal control problem and dynamic programming
   b) Model Predictive Control for Linear Systems
   c) General MPC Theory (Closed-loop stability, recursive feasibility)
7. **Advanced topics (if time permits)**
   a) Iterative LQR (iLQR)
   b) Differential Dynamic Programming (DDP)
   c) Numerical optimal control (direct and indirect methods, collocation)

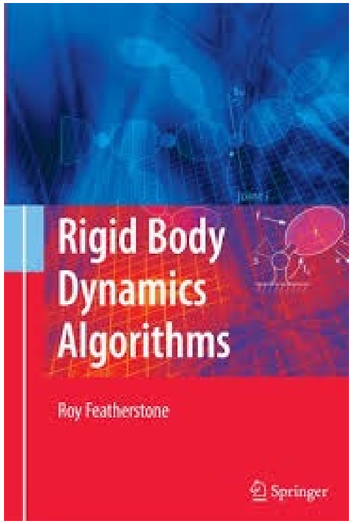
Prerequisite:

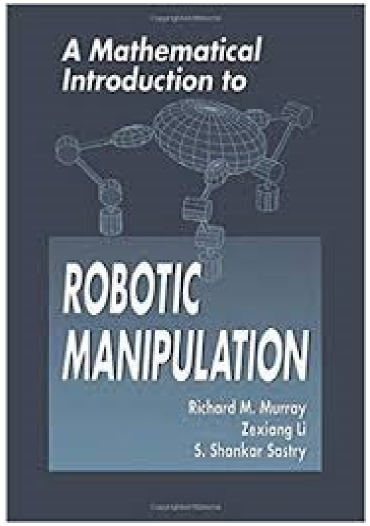
- Introduction to robotics
  - Solid background in rigid body kinematics and dynamics in the level described in standard beginner textbooks, such as:
    - "Introduction to Robotics: Mechanics and Control", J. Craig
    - "Robot Modeling and Control", M. Spong, S. Hutchinton, and M. Vidyasagar
- Undergraduate class in control
- Maturity in math, solid understanding in linear algebra (see tutorial notes in linear algebra), good at abstract reasoning
- Programming skills: **Python** & Matlab
  - Involve Python coding with Drake for some assignments

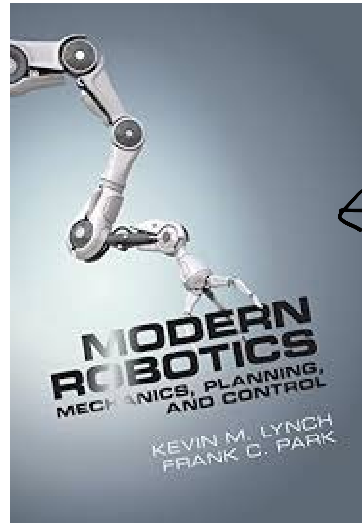
- **Grading:**

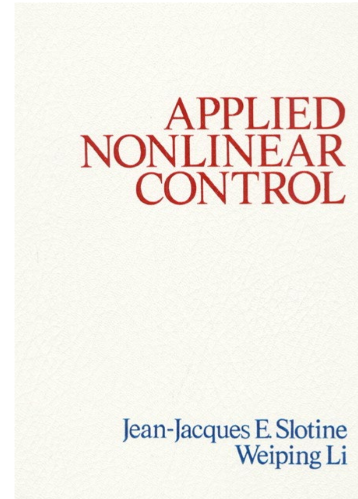
Homework	20%
Mini-Project	15%
Quiz	10%
Midterm	25%
Final Exam	30%

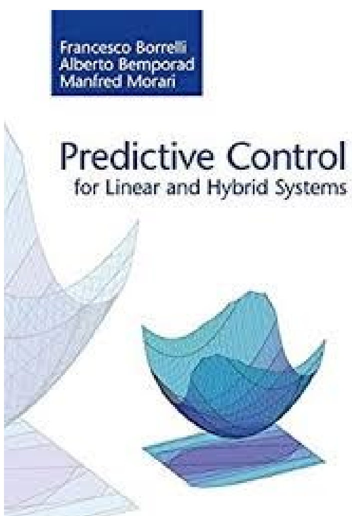
References:

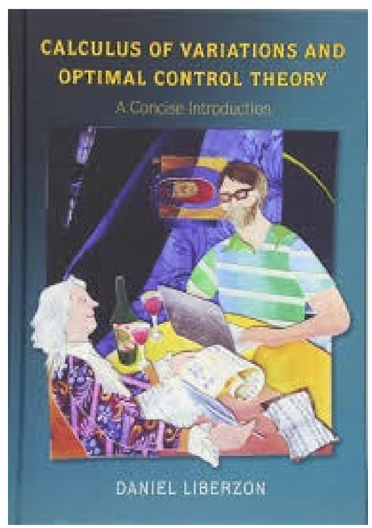

Rigid Body Dynamics Algorithms
Roy Featherstone
Springer

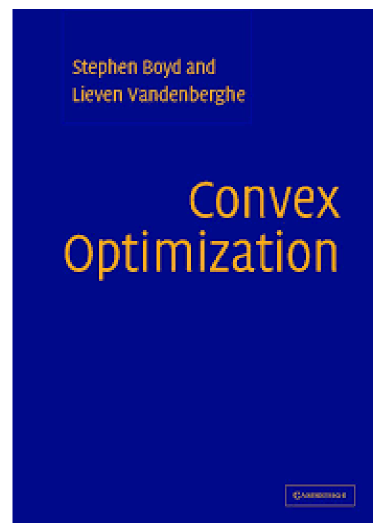

A Mathematical Introduction to
ROBOTIC MANIPULATION
Richard M. Murray
Zexiang Li
S. Shankar Sastry


MODERN ROBOTICS
MECHANICS, PLANNING, AND CONTROL
KEVIN M. LYNCH
FRANK C. PARK


APPLIED NONLINEAR CONTROL
Jean-Jacques E. Slotine
Weiping Li


Francesco Borrelli
Alberto Bemporad
Manfred Morari
Predictive Control
for Linear and Hybrid Systems


CALCULUS OF VARIATIONS AND OPTIMAL CONTROL THEORY
A Concise Introduction
DANIEL LIBERZON


Stephen Boyd and
Lieven Vandenberghe
Convex Optimization

References:

- "Mathematical introduction to robotic manipulation", R. Murray, Z. Li, S. Sastry
  https://www.cds.caltech.edu/~murray/books/MLS/pdf/mls94-complete.pdf

- "Modern Robotics: Mechanics, Planning, and Control", Kevin M. Lynch and Frank C. Park, Cambridge University Press, 2017, ISBN 9781107156302
  http://hades.mech.northwestern.edu/index.php/Modern_Robotics

- "Rigid Body Dynamics Algorithms", Roy Featherston https://www.springer.com/gp/book/9780387743141

- "Applied Nonlinear Control", Slotine & Li

- "Predictive Control for Linear and Hybrid Systems", F. Borrelli, A. Bemporad, M. Morari, Cambridge University Press , July, 2017

- http://www.mpc.berkeley.edu/mpc-course-material

- "Calculus of Variations and Optimal Control Theory: A Concise Introduction", Daniel Liberzon, Princeton University Press, 2011

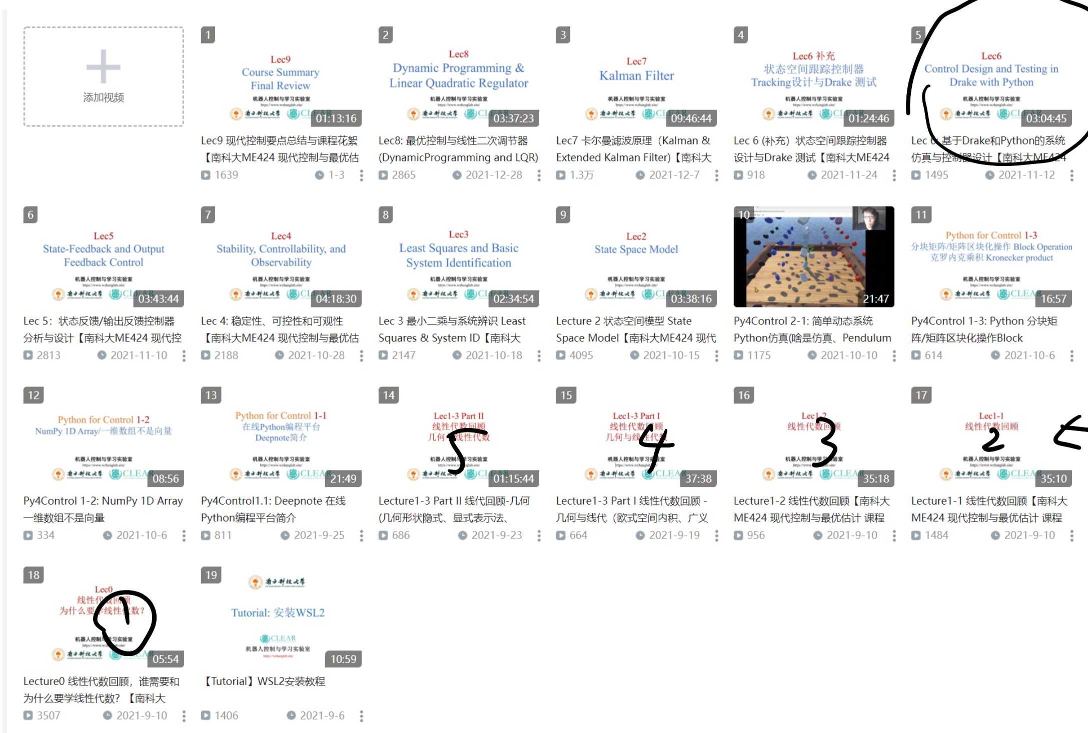
- http://liberzon.csl.illinois.edu/teaching/cvoc/cvoc.html

- "Convex optimization", Stephen Boyd, Cambridge University Press
  https://web.stanford.edu/~boyd/cvxbook/

- Lecture notes, and papers distributed in class.

Prerequisite and Background Reading:

- “Linear Algebra Review and Reference”, Zico Kolter
- “The Matrix Cook Book” - Kaare Brandt Petersen, Michael Syskind Pedersen
- “Some Notes on Advanced Calculus”, Nathan Ratliff



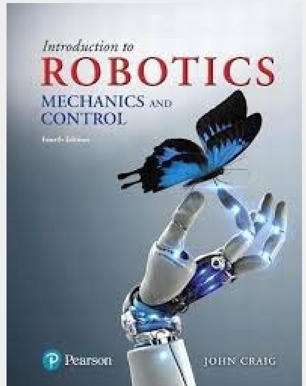
https://space.bilibili.com/474380277/channel/seriesdetail?sid=291615

How to learn robotics?

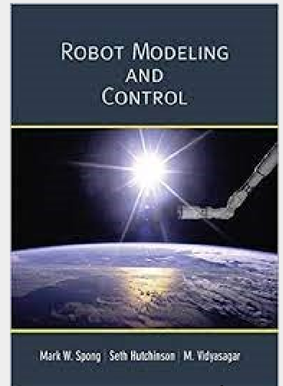
Analogous to Math Analysis

Undergraduate

- D-H based kinematics
- Lack of solid training on dynamics



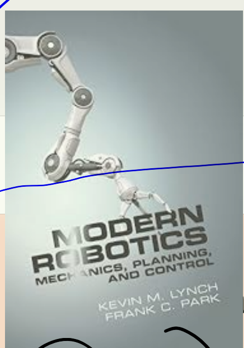
Craig



Spong

Non-math major

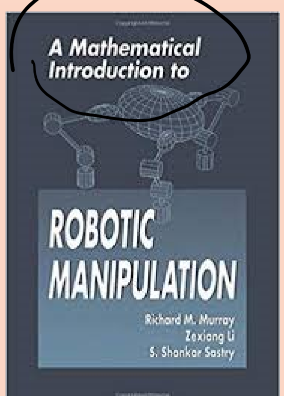
Calculus



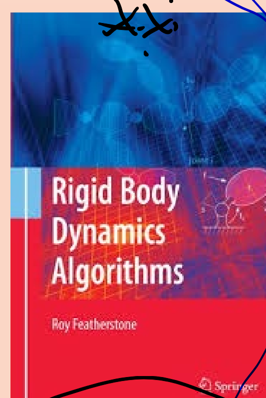
Lynch & Park

duate level

Screw theory & PoE based kinematics and dynamics



Murray, Li, & Sastry

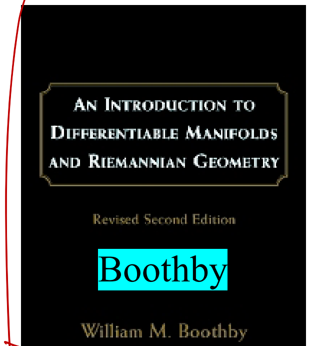


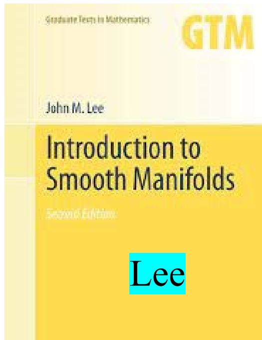
Featherstone

Math major

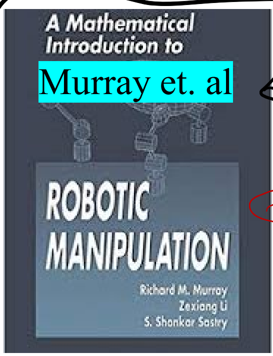
Real Analysis

- **How to learn advanced kinematics and dynamics?**

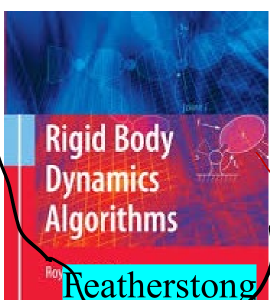


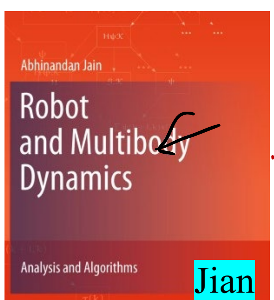


Differential geometry, manifolds, tangent space, cotangent space, differential forms, Lie groups, Lie algebra, Lie bracket, Riemannian metric, adjoint operator



Screw axis, twist, exponential coordinate, wrench, product of exponential, multibody dynamics, Newton-Euler Equation





Spatial velocity, spatial acceleration, spatial cross product …,