Syllabus: Robot Dynamics and Control
ME 446 / ECE 489 / SE 422
Spring 2021

Course Summary and learning objectives:

This course is intended for seniors and first year graduate students from a wide variety of engineering disciplines. We will emphasize the basics of motion and force control mostly for serial robotic manipulators. Transformations from task space to joint space will allow joint level control. The study of forward and inverse kinematics, along with differential kinematics will provide a foundation for designing robots and their controllers. We will examine robots operating in free spaces as well as in contact with environments. Advanced topics will look at the dynamics and control of other underactuated and mobile robotic systems. It is assumed the students have a basic knowledge of rigid-body dynamics and linear control theory, including feedback and feedforward control. This is a hands-on course multiple lab sections. Students are expected to study independently and work on their projects outside of class. It is very helpful if students have already taken Introduction to Robotics (ME445/ECE470/AE482).

Course webpages

Lecture: Compass2g
Lab: http://coecsl.ece.illinois.edu/ME446/

Instructors:

Lecture: Joao Ramos jlramos@illinois.edu – Office hours: TBD @ 163 CAB
Lab: Dan Block d-block@illinois.edu – Office hours: Arrange as needed

Teaching Assistants:

Yanran Ding yding35@illinois.edu – Office hours: TBD @ TBD
Open lab office hours:

Lecture and lab hours:

Lecture: Tuesdays and Thursdays 9:30-10:50am @ at:
Lab Section 1: Mondays 2-5pm @ room 3071 ECE Building
Lab Section 2: Wednesdays 11-2pm @ room 3071 ECE Building
Lab Section 3: Fridays 10am-1pm @ room 3071 ECE Building

Text book:

Robot Modeling and Control - Spong, Hutchinson & Vidyasagar – Wiley
Other suggested: *Modern Robotics: Mechanics, Planning, and Control* – Lynch and Park, 2017

Grading:

Homework: 50%
Lab participation and reports: 30%
Final Project: 20%

Course schedule:

Week	Class	Day	Lecture topics	Lab topics	Comments
1	1	Jan 26	Class intro Robot examples	-	
		Jan 27	-	Lab 1A: Kinematics	
	2	Jan 28	Rigid-body, DoF, Rotation and HTMs	-	
2	3	Feb 02	Forward Kin. (DH par.) Inverse Kinematics Workspace	-	
		Feb 03	-	Lab 1B: Kinematics	HW 1 due
	4	Feb 04	Differential kinematics Jacobian derivation Manipulability	-	
3	5	Feb 09	Lagrange EoM Kin. and Pot. energy Inertia tensor Reflected inertia	-	
		Feb 10	-	Lab 1A: Kinematics	HW 2 due
	6	Feb 11	Manipulator Equation Examples and properties Forward and inverse dynamics	-	
4	7	Feb 16	Newton-Euler algorithm Numerical Simulation Discrete control and filtering	-	
		Feb 17	-	Break day	HW 3 due No Lab this week Make up time
	8	Feb 18	Typical actuators DC motor dynamics and limitations Transmission dynamics and friction Force Ellipsoid	-	
5	9	Feb 23	Joint PD control Selecting gains Practical considerations	-	
		Feb 24	-	Lab 1B: Kinematics	HW 4 due Lab report 1A due
	10	Feb 25	Joint PID control Feedforward control PD control + feedforward	-	
6	11	Mar 02	Single joint PD demo Q&A	-	
		Mar 03	-	Lab 2A: Joint Control	HW 5 due Lab report 1B due
	12	Mar 04	Path and trajectory generation and planning	-	
7	13	Mar 09	PD + gravity compensation Inverse dynamics control	-	

		Mar 10	-	Lab 2B: Joint Control	HW 6 due
	14	Mar 11	Multi-joint Control Demo Semi-static force control	-	
8	15	Mar 16	Hybrid systems Impact dynamics (IMF) Contact models (soft and hard)	-	
		Mar 17	-	Lab 2A: Joint Control	HW 7 due
	16	Mar 18	Stiffness and compliance Impedance control	-	
9	-	Mar 23	Hybrid Force/Velocity control Adaptive control	-	
		Mar 24	-	Break day / Lab 2B: Joint Control	Lab report 2A due, Lab 2B will have to reschedule Wed lab this week
	-	Mar 25	Trajectory optimization	-	
10	17	Mar 30	Optimization-based Control	-	
		Mar 31	-	Lab 3A: Task Control	HW 8 due Lab report 2B due
	18	April 01	Actuation and Sensing	-	
11	19	April 06	Design Considerations	-	
		Apr 07	-	Lab 3B: Task Control	Lab report 3A due
	20	Apr 08	Underactuated robots	-	
12	21	Apr 13	Break day	-	
		Apr 14	-	Break day	Lab report 3B due, No Lab this week Make up time
	22	Apr 15	Q&A for project	-	
13	23	Apr 20	Floating base Legged locomotion Simple models	-	
		Apr 21	-	Lab 4A: Project workday	HW 9 due
	24	Apr 22	Discuss HW 9	-	
14	25	Apr 27	Other robots (parallel, mobile, soft,…)	-	
		Apr 28	-	Lab 4B: Project workday	
	26	Apr 29	Semester recap	-	
15	27	May 04	-	-	
		May 05	-	Final project demo A Final project demo B	
	28	May 06	-	-	
16	29	May 11	Reading day	-	
		May 12	-	Make up times	Final reports A due Final report B due
	30	May 13	Reading day	-	

<u>Homework and lab report contents:</u>

HW	Homework content	Lab	Laboratory content
	-	1	• DSP controller • Code Composer Studio IDE • CRS robot arm
1	• Coordinate frames • DH analysis • Calculate HTM's	1	• Implement FK and IK on CRS robot arm
2	• Calculate FK and IK • Code for plotting robot position • Convert joint <-> task space trajectory • Manipulability, workspace		
3	• Calculate Kin and Pot energies • Calculate equations of motion	2	• Implement velocity and integration calculations online • Implement joint PD/PID
4	• Simulate the robot on MatLab • Open-loop sim: gravity, friction, damping • Velocity and integration from real data		
5	• Reflected inertia, force capability • Actuator pos control w/ voltage and current • Motor model on simulation (saturation and inertia) • Simulate point-to-point PD/PID	2	• Implement joint PD + FF • Implement gravity compensation • Implement joint trajectory tracking
6	• Simulate gravity compensation • Trajectory generation (filtered step for point-to-point) • Simulate point-to-point feedforward joint control • Simulate joint trajectory tracking • Evaluate power consumption		
7	• Inverse dynamics control with joint space tracking • Compare inverse dynamics control with PD+FF using payload at end-effector	3	• Task space PD/PID/FF • Task space impedance • Task space force • Straight line trajectory tracking
8	• Simulate task space PD and FF control • Simulate task space force control • Simulate task space impedance control		
9	In simulation: • position control: point-to-point, sequence of points, and trajectory. Use laser pointers • impedance control: soft/rigid in different directions • force control: approach a surface, detect, and press with prescribed force	4	Final project workday
10	Bonus challenge problem: • Trajectory optimization • Optimization-based controller • Underactuated robots • …?	5	Final project demo Extra points on demo day: • Minimize time • Minimize power

Homework and report evaluation:

- Reports must include:
  - the complete derivations;
  - code utilized;
  - limitations, difficulties and failures.
  - Nice and informative figures.
- Extra points for creative and innovative ideas.

Useful references for robot dynamics and control:

- Modern Robotics book: http://hades.mech.northwestern.edu/images/7/7f/MR.pdf
- Northwestern robotics: https://www.youtube.com/user/kevinl2145/playlists?view=50&sort=dd&shelf_id=9
- Roy Featherstone's page: http://royfeatherstone.org/
- Rigid-body dynamics algorithms book: https://link.springer.com/book/10.1007%2F978-1-4899-7560-7
- MIT Underactuated robotics notes: http://underactuated.mit.edu/underactuated.html
- MIT Underactuated robotics channel: https://www.youtube.com/channel/UChfUOAhz7ynELF-s_1LPpWg
- Notre-Dame Intro to robotics: http://sites.nd.edu/pwensing/ame-50551-introduction-to-robotics/
- Notre-Dame optimization-based robotics: http://sites.nd.edu/pwensing/ame-60621/
- IHMC robotics channel: https://www.youtube.com/user/humanoidroboticschan/videos
- MATLAB control systems in practice series: https://www.youtube.com/watch?v=ApMz1-MK9IQ&list=PLn8PRpmsu08pFBqgd_6Bi7msgkWFKL33b
- HEBI Robotics IROS 2020 tutorial: https://www.youtube.com/playlist?list=PLYy-ocPrXDOUovtgclU7kgqqlnC1-Nzfr