Syllabus: Robot Dynamics and Control
ME 446 / ECE 489 / SE 422 AL, Spring 2024
Time: TR 9:30am–10:50am
Room: 144 Loomis Laboratory

Course Summary:
This course is cross listed between the Departments of Mechanical Science and Engineering, Electrical and Computer Engineering, and Industrial & Enterprise Systems Engineering. It is intended for seniors and first year graduate students from a wide variety of engineering disciplines and backgrounds. The course will emphasize the fundamentals of kinematics, dynamics, and motion and force control of robots and with focus on serial manipulators (robot arm). 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 space 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 with 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).

Learning objectives:
By the end of this course, you will be able to:
- Model and analyze the kinematics and dynamics of robots
- Design motion and force controllers based on mathematical models of robots
- Implement theoretical concepts of signal processing and controls in real robots
- Work with real robot hardware

Course webpages:
- Lecture: https://canvas.illinois.edu/courses/43348
- Lab: http://coecsl.ece.illinois.edu/ME446/

Instructors:
- Lecture: Justin Yim jkyim@illinois.edu – Office: 4411 Mechanical Engineering Lab (MEL) Office hours: TBD or by appointment @ 4411 MEL and @ Zoom: https://illinois.zoom.us/j/82499442623?pwd=VVQ2R1BqdzNzcVpQRnFvM1I5b1hEZz09
- Lab: Dan Block d-block@illinois.edu – Office hours: by appointment @ 3071 ECE Bldg

Teaching Assistants:
- Nagesh Eranki neranki2@illinois.edu – Office hours: TBD @ TBD
- Negin Musavi: nmusavi2@illinois.edu – Office hours: TBD @ TBD

Lecture and lab hours:
- Lecture: Tuesdays and Thursdays 9:30-10:50am @ 144 Loomis Laboratory
- Lab Section 1 (AB1): Friday 12:00pm – 2:50pm @ room 3071 ECE Bldg

- Lab Section 2 (AB2): Wednesday 11:00am – 1:50pm @ room 3071 ECE Bldg
- Lab Section 3 (AB3): Friday 09:00am – 11:50am @ room 3071 ECE Bldg

Textbooks:

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

Grading breakdown:

- Homework and lecture participation: 30%
- Midterm: 20%
- Lab participation and reports: 30%
- Final project demo and report: 20%

Grading scheme:

- 90% "A-" is guaranteed
- 80–89.9% "B-" is guaranteed
- 70–79.9% "C-" is guaranteed
- 60–69.9% "D-" is guaranteed
- <60% "F"

Homework and lab report evaluation:

- There will be approximately ten homework assignments during the course.
- Homework will be turned in virtually (in .pdf format only) via canvas by the deadline.
- The lowest homework grade will be dropped.
- **No late homework will be accepted without documented justification.**
- Complete homework and lab reports must include:
    - Clear demonstration of formulas and concepts used.
    - Complete and neat mathematical derivations to obtain the final answer.
    - MATLAB (or other) source code used.
    - Neat and informative figures, tables, and diagrams with proper labels and units.

Examination:

- One midterm is scheduled tentatively at March 9th at regular lecture time/location.
- You can bring one A4 sheet of paper with personal notes (front and back).
- Requests for a conflict or make-up examination will be individually evaluated. Only requests that, in the instructor's opinion, are fully justified (i.e., with appropriate written documentation) will be granted.
- Students can ONLY request a re-grading of their exams within the first 48 hours of receipt of their midterm. Note that re-graded exams may potentially receive a lower grade, if applicable.

Final project demonstration:

In the end of the course, students will control a real manipulator to complete a series of physical tasks such as inserting a peg in the whole or pushing buttons. Students will demonstrate the capabilities of their algorithms during a friendly competition that will award the fastest and the most accurate robot.

Course schedule:

Week	Class	Day	Lecture topics	Lab topics	Comments
1	1	Jan 16	Class intro Robot examples	-	
		Jan 17	-	-	No lab this week
	2	Jan 18	Rigid-body, DoF, Rotation and HTMs	-	
2	3	Jan 23	HTM's Forward Kin. (DH par.)	-	HW 1 released
		Jan 24	-	Lab 1	
	4	Jan 25	Workspace Inverse Kinematics Diff. Kin. (Analytical Jacob.)	-	
3	5	Jan 30	Manipulability Ellipsoid Singularity General Jacobian form Jacobian computation	-	HW 1 due HW 2 released
		Jan 31	-	Lab 1	
	6	Feb 01	Jacobian in MATLAB Jacobian and statics Lagrangian formulation Lagrangian examples	-	
4	7	Feb 06	Kin & Pot energy Inertia Tensor Task-space inertia Manipulator equation	-	HW 2 due HW 3 released
		Feb 07	-	Lab 1	
	8	Feb 08	EoM example (linear) EoM example (rotary) EoM MATLAB	-	
5	9	Feb 13	Properties of M(q) FD and ID Numerical Simulation	-	HW 3 due HW 4 released
		Feb 14	-	Lab 2	
	10	Feb 15	Newton-Euler Formulation	-	
6	11	Feb 20	Motor and transmission dynamics	-	HW 4 due HW 5 released
		Feb 21	-	Lab 2	
	12	Feb 22	Joint PD control Practical considerations	-	
7	13	Feb 27	Joint PID control Feedforward control PD control + feedforward	-	HW 5 due
		Feb 28	-	Lab 2	
	14	Feb 29	Midterm review	-	
8	15	Mar 05	Lecture cancelled	-	
		Mar 06	-	Lab 3	
	16	Mar 07	Midterm (up to HW5)	-	
9	-	Mar 12			

		Mar 13	Spring Break		
	-	Mar 14			
10	17	Mar 19	Midterm solution review CRS robot simulator	-	HW 6 released
		Mar 20	-	Lab 3	
	18	Mar 21	Path and trajectory generation and planning	-	
11	19	Mar 26	PD + gravity compensation Inverse dynamics control	-	
		Mar 27	-	Lab 3	
	20	Mar 28	Semi-static force control Task-space Inv. Dyn. control	-	HW 6 due HW 7 released
12	21	Apr 02	Stiffness and compliance Impedance control	-	
		Apr 03	-	Lab 4	
	22	Apr 04	Hybrid systems Impact dynamics Contact models	-	HW 7 due HW 8 released
13	23	Apr 09	Impact and contact Sim Control constraints	-	
		Apr 10	-	Lab 4	
	24	Apr 11	Hybrid F/V Control	-	HW 8 due HW 9 released
14	25	Apr 16	Potential fields Adaptive control Other adv. controls	-	
		Apr 17	-	Final Project workday	
	26	Apr 18	Trajectory optimization Worked example	-	HW 9 due HW 10 released
15	27	Apr 23	Traj. optimization example Optimization-based control	-	
		Apr 24	-	Final Project workday	
	28	Apr 25	Underactuated robots Linearization Partial Feedback Lin	-	HW 10 due Extra HW 11 released
16	29	Apr 30	Semester review	-	
		May 01	-	Final Project workday	Last day of instruction
	-	May 02	-	-	HW 11 due
17	-	May 07	-	Final Project Demo 7:00pm – 10:00pm	

Useful references for robot dynamics and control:

- Modern Robotics book
- Northwestern robotics
- Roy Featherstone's page
- Rigid-body dynamics algorithms book
- MIT Underactuated robotics notes
- MIT Underactuated robotics channel
- Notre-Dame Intro to robotics
- Notre-Dame optimization-based robotics
- IHMC robotics channel
- MATLAB control systems in practice series
- HEBI Robotics IROS 2020 tutorial
- Steve Brunton YouTube Channel

Course policies:

1. Please show respect for your classmates by limiting distractive behavior. Turn your cell phones off during class and please keep any side discussions short and quiet.
2. You are expected to adhere to all of the rules pertaining to academic integrity outlined in the Student Code. Failure to do so will result in an automatic F for the course.
3. It is expected that each student will be courteous and respectful to all members of the class and will carry him or herself in an orderly manner for the entire duration of the course as outlined in the Student Code.
4. Regular class attendance and punctuality are expected. However, do not come to class if you are sick and potentially contagious.
5. You are encouraged to discuss homework problems with your fellow classmates. But your final answers should be based on your own understanding. Copying other's work is NOT acceptable.

Special Accommodations:

If you have any condition, such as a physical or learning disability, which will make it difficult for you to carry out the work as it has been outlined or which will require special accommodations, please notify the instructor during the first week of the course with the appropriate written documentation. To contact the Division of Rehabilitation-Education Services (DRES), you may visit 1207 S. Oak St., Champaign, IL 61820, call (217) 333-1970, or email disability@illinois.edu.

Absences and Conflicts

If you have a conflict with a course activity due to religious practices and observances, work travel, or similar reason, email the professor as early as possible and no later than one week (seven days) in advance of the conflict. If an unplanned event such as an illness or family emergency impacts your ability to attend class or complete assignments, arrangements must be made with the professor via email as soon as practical.

Mental Health

Significant stress, mood changes, excessive worry, substance/alcohol misuse or interferences in eating or sleep can have an impact on academic performance, social development, and emotional wellbeing. The

University of Illinois offers a variety of confidential services including individual and group counseling, crisis intervention, psychiatric services, and specialized screenings which are covered through the Student Health Fee. If you or someone you know experiences any of the above mental health concerns, it is strongly encouraged to contact or visit any of the University's resources provided below. Getting help is a smart and courageous thing to do for yourself and for those who care about you.

- Counseling Center (217) 333-3704
- McKinley Health Center (217) 333-2700
- National Suicide Prevention Lifeline (800) 273-8255
- Rosecrance Crisis Line (217) 359-4141 (available 24/7, 365 days a year)

If you are in immediate danger, call 911.

Run > Hide > Fight

Emergencies can happen anywhere and at any time. It is important that we take a minute to prepare for a situation in which our safety or even our lives could depend on our ability to react quickly. When we're faced with almost any kind of emergency – like severe weather or if someone is trying to hurt you – we have three options: Run, hide or fight.

Run

Leaving the area quickly is the best option if it is safe to do so.

- Take time now to learn the different ways to leave your building.
- Leave personal items behind.
- Assist those who need help, but consider whether doing so puts yourself at risk.
- Alert authorities of the emergency when it is safe to do so.

Hide

When you can't or don't want to run, take shelter indoors.

- Take time now to learn different ways to seek shelter in your building.
- If severe weather is imminent, go to the nearest indoor storm refuge area.
- If someone is trying to hurt you and you can't evacuate, get to a place where you can't be seen, lock or barricade your area if possible, silence your phone, don't make any noise and don't come out until you receive an Illini-Alert indicating it is safe to do so.

Fight

As a last resort, you may need to fight to increase your chances of survival.

- Think about what kind of common items are in your area which you can use to defend yourself.
- Team up with others to fight if the situation allows.
- Mentally prepare yourself – you may be in a fight for your life.

Please be aware of people with disabilities who may need additional assistance in emergency situations.

Other resources

- **police.illinois.edu/safe** for more information on how to prepare for emergencies, including how to run, hide or fight and building floor plans that can show you safe areas.
- **emergency.illinois.edu** to sign up for Illini-Alert text messages.
- **Follow the University of Illinois Police Department** on Twitter and Facebook to get regular updates about campus safety.