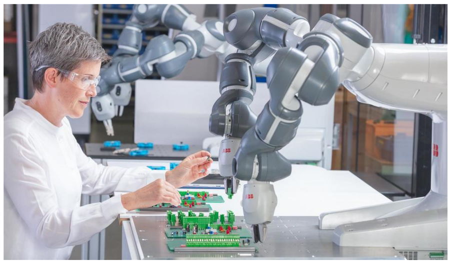
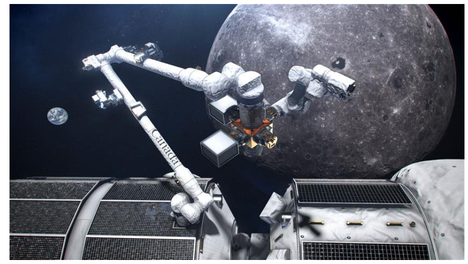
ECE 486 / 780 T03 Robot Dynamics & Control
Spring 2024





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Teaching assistants	Tutorials	Prajwal Thakur	prajwal.thakur@uwaterloo.ca
	Lab	Amr Hamdi	amhamdi@uwaterloo.ca

Time and place	Lectures	Tuesday, Thursday 13:00–14:20, E7 4433
	Tutorials	Tuesday 20:00–20:50, E7 4433
	Office hours	Wednesday 14:00–16:00, E5 4006

Website	`learn.uwaterloo.ca/`
	`https://piazza.com/uwaterloo.ca/summer2024/ece486ece780t03`
	`https://www.gnotomista.com/teaching.html`

Description
This course will introduce students to dynamic modeling and control techniques for robotic systems, and expose them to some cutting-edge research. The course will be divided into five modules, corresponding to the following topics:

1. Dynamics of manipulators
2. Control of manipulators
3. Kinematics of mobile robots
4. Control of mobile robots
5. Optimization-based robot control

Each module will be presented during lectures supported by interactive demonstrations with the Franka Emika manipulator robot (`https://www.franka.de/research`) in the RoboHub. The concepts will be reinforced through homeworks containing both theoretical exercises and programming assignments (Python or MATLAB). The course will also include a lab section (for undergraduate students only) and a project which will allow students to implement robot control algorithms on a table-top robotic arm and the mobile manipulator DJI RoboMaster EP (`https://www.dji.com/ca/robomaster-ep`), respectively.

Prerequisites

- ECE 380 for ECE 486
- No formal prerequisites for ECE 780 T03

Prior knowledge of linear algebra, rigid body dynamics, feedback control systems, and mathematical optimization can make life a bit easier.

Reading

The course textbook is:

[1] Mark Spong, Seth Hutchinson, and Mathukumalli Vidyasagar, *Robot modeling and control*, John Wiley & Sons, 2020

The following texts will be used for parts of the course:

[2] Bruno Siciliano, Lorenzo Sciavicco, Luigi Villani, and Giuseppe Oriolo, *Robotics. Modelling, planning and control*, Springer, 2009

[3] Stephen Boyd and Lieven Vandenberghe, *Convex optimization*, Cambridge University Press, 2004

[4] Magnus Egerstedt, *Robot Ecology: Constraint-Based Design for Long-Duration Autonomy*, Princeton University Press, 2021

Additional reading material will be provided as appropriate.

Deliverables and grading

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- Homeworks (20%)
  - 4 homeworks
  - 5% each
- Midterm (30%)
- Lab (30%)
  - Labs 1, 2, 3, 4, 5 are worth 4%, 7%, 7%, 6%, 6%, respectively
- Project (20%)
  - Final project report: 15%
  - Project code: 5%

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- Homeworks (50%)
  - 4 homeworks
  - 12.5% each
- Lecturing (10%)
- Project (40%)
  - Midterm project report: 10%
  - Final project report: 20%
  - Project code: 10%

Lab details

The lab will consist of the implementation of forward and inverse kinematics algorithms on a DOBOT Magician desktop robotic arm, programmed in Python. The first lab is an introduction to the programming environment of the robot. The second and third labs are focused on direct and inverse kinematics. The fourth and firth labs consist of a drawing task. The work will be carried out in groups of at most 2 people (same groups of the project). More details in the lab manual on the course website.

Lecturing details

The lecturing deliverable will consist in a 10-minute presentation of a topic not covered in class and independently studied. Preparation and delivery of the presentation will be carried out in groups of at most 2 people (same groups of the project).

Project details

The project will consist of a mobile manipulation task using the DJI RoboMaster EP programmed in Python. The deliverables will be three:

1. A midterm report, in the form a PDF document of maximum 2 pages, describing the progress made and the results obtained so far
2. A final report, in the form of a PDF document of maximum 4 pages, structured as follows:
   - Section I: Proposed approach
   - Section II: Results
   - Section III: Discussion
3. The code developed to complete the project

The work will be carried out in groups of at most 2 people (same as lab groups or lecturing groups). The reports must be accompanied by the detailed description of the work carried out by each member of the group, including what sections of each report were written by whom. The reports must be formatted using the IEEE conference template (`https://www.ieee.org/conferences/publishing/templates.html`). More details in the project description on the course website.

Project details: Alternative for MASc students

The project will consist of the solution to a problem in the student's research area using the techniques covered during the course. The deliverables will be four:

1. A proposal, in the form of a 1-page PDF document, structured as follows:
   - Section I: Problem description
   - Section II: Novelty and/or impact
   - Section III: How robot dynamics and control techniques play a key role
   - Section IV: Technical challenges
   - Section V: Metric for success
   - Section VI: Timeline
2. A midterm report, in the form a PDF document of maximum 2 pages, describing the progress made and the results obtained so far
3. A final report, in the form of a PDF document of maximum 4 pages, structured as follows:
   - Section I: Introduction
   - Section II: Literature review
   - Section III: Materials and methods
   - Section IV: Results
   - Section V: Discussion
4. The code developed to complete the project

Additionally, a short video (maximum 1 minute) to supplement the results may also be attached. All documents must be formatted using the IEEE conference template (`https://www.ieee.org/conferences/publishing/templates.html`).

Audit policy

Either the homeworks or the project must be completed to audit the course.

Policy on academic integrity

Academic integrity To maintain a culture of academic integrity, members of the University of Waterloo are expected to promote honesty, trust, fairness, respect and responsibility. A student is expected to know what constitutes academic integrity, to avoid committing academic offences, and to take responsibility for their actions. A student who is unsure whether an action constitutes an offence, or who needs help in learning how to avoid offences (e.g., plagiarism, cheating) or about "rules" for group work/collaboration should seek guidance from course instructor, academic advisor, or Graduate Associate Dean. When misconduct has been found to have occurred, disciplinary penalties will be imposed under Policy 71 - Student Discipline. For information on categories of offenses and types of penalties, students should refer to Policy 71 - Student Discipline, `https://uwaterloo.ca/secretariat/policies-procedures-guidelines/policy-71`.

Grievance A student who believes that a decision affecting some aspect of their University life has been unfair or unreasonable may have grounds for initiating a grievance. Read Policy 70 - Student Petitions and Grievances, Section 4, `https://uwaterloo.ca/secretariat/policies-procedures-guidelines/policy-70`.

Discipline A student is expected to know what constitutes academic integrity (`https://uwaterloo.ca/academic-integrity`) to avoid committing an academic offence, and to take responsibility for his/her actions. A student who is unsure whether an action constitutes an offence, or who needs help in learning how to avoid offences (e.g., plagiarism, cheating) or about "rules" for group work/collaboration should seek guidance from the course instructor, academic advisor, or the undergraduate Associate Dean.

Appeals A student may appeal the finding and/or penalty in a decision made under Policy 70 - Student Petitions and Grievances (other than regarding a petition) or Policy 71 - Student Discipline if a ground for an appeal can be established. Read Policy 72 - Student Appeals, `https://uwaterloo.ca/secretariat/policies-procedures-guidelines/policy-72`.

Note for students with disabilities The Office for persons with Disabilities (OPD), located in Needles Hall, Room 1132, collaborates with all academic departments to arrange appropriate accommodations for students with disabilities without compromising the academic integrity of the curriculum. If you require academic accommodations to lessen the impact of your disability, please register with the OPD at the beginning of each academic term.

Academic Integrity Office (UW) `https://uwaterloo.ca/academic-integrity/`.

Schedule

Date	Subject	Reading	Deliverable due
	DYNAMICS OF MANIPULATORS		
May 7	Introduction to robot dynamics and control		
May 9	Rigid body transformations	2 [1], 2 [2]	
May 14	Direct kinematics	4 [1], 3 [2]	
May 16	Differential kinematics	3 [1], 2 [2]	
May 21	**Monday schedule — no class**		
May 23	Inverse kinematics	5 [1], 3 [2]	
	CONTROL OF MANIPULATORS		
May 28	Dynamic model of manipulators	6 [1], 7 [2]	Lecturing, project proposal
May 30	Decentralized and centralized control	8, 9 [1], 8 [2]	Lecturing, HW1
May 31			Lab 1
Jun 4	Operational space control	9 [1], 8 [2]	
Jun 5	Robohub session, 11:30–13:30		
Jun 6	Impedance control	9 [1], 8 [2]	
	KINEMATICS OF MOBILE ROBOTS		
Jun 11	Kinematic constraints	14 [1], 11 [2]	HW2
Jun 13	Kinematic model	14 [1], 11 [2]	Lab 2
Jun 17-21	**Midterm week — no class**		
Jun 19	**Midterm exam, 10:00–11:15, E5 4106/4128**		
Jun 19	Robohub session, 13:30–15:30		
	CONTROL OF MOBILE ROBOTS		
Jun 25	Controllability	14 [1], 11 [2]	
Jun 27	Control of driftless systems	14 [1], 11 [2]	Midterm project report
Jun 28			Lab 3
Jul 2	Differential flatness	14 [1], 11 [2]	HW3
Jul 4	Control of differentially flat systems	14 [1], 11 [2]	
	OPTIMIZATION-BASED ROBOT CONTROL		
Jul 9	Recap of mathematical optimization	1 [3], lecture notes	
Jul 11	Constrained convex optimization	4, 5 [3], lecture notes	Lab 4
Jul 16	Stability and control Lyapunov functions	4 [4], lecture notes	HW4
Jul 17	Robohub session, 11:30–13:30		
Jul 18	Invariance and control barrier functions	4 [4], lecture notes	Lab 5
Jul 23	Combining stability and invariance tasks	4 [4], lecture notes	
Jul 24	Robohub session, 11:30–13:30		
Jul 25	Research challenges and opportunities		
Jul 28			Final project report
Jul 30	Robohub demo		