

ME 458 Syllabus – 26 Spring



Introduction to Feedback Control of Autonomous Systems

Course Information

Number and Name

ME 458 - Introduction to Feedback Control of Autonomous Systems

Instructor

Prof. Xiangru Xu, Assistant Professor, Department of Mechanical Engineering, UW-Madison

Office: ME 2035

Email: xiangru.xu@wisc.edu

Office hours: Monday & Wednesday 4:00-5:00 PM, ME2035. Additional office hours may be scheduled by appointment.

Lecture Meeting Time & Location

Lecture time: Monday & Wednesday 2:30-3:45pm

Lecture location: ME 1143

Canvas

<https://canvas.wisc.edu/courses/498694>

Instruction Mode

In person

Credit

This is a three-credit course with two 75-min lectures per week.

Course Description

This course introduces feedback control fundamentals and numerical optimal control algorithms that underpin autonomous robotic systems. Topics to be covered:

- Feedback Control Fundamentals: state-space modeling, Lyapunov stability, controllability & stabilizability of LTI systems, control Lyapunov functions.
- Numerical Optimal Control Algorithms: optimal control theory, direct method, indirect method, linear quadratic regulator, dynamic programming, model predictive control.
- Control and Planning of Quadcopters: kinematics & dynamics, state estimation, control and motion planning.

Prerequisites

M E 340, E C E 332 / 334, or graduate/professional standing.

Learning Outcome

Upon completion of the course, you will be able to

1. Express a dynamic system into its state space form and determine its linearized model around a given operating point
2. Use Lyapunov direct and indirect methods to determine the stability of nonlinear systems
3. Explain and assess controllability, observability, and stability of linear systems
4. Apply the maximum principle to find the optimal solution of an unconstrained optimal control problem
5. Solve general optimal control problems using off-the-shelf numerical software
6. Solve linear quadratic problems using linear quadratic regulator
7. Apply differential flatness for quadcopter trajectory generation, and design linear tracking controllers for quadcopters

Grading & Assignments

Grading

The course will be graded based on students' performance on homework, midterm exams, and final project. Attendance and participation are highly encouraged but will not be part of the grading. Grades will be posted on the Canvas website.

Note: Score-related questions must be raised within 48 hours of receiving the score.

Grading Weights:

Homework	20%
Midterm Exam 1	25%
Midterm Exam 2	25%
Final Project	25%
Participation	5%

Grading Scale:

Point range	Grade
90 - 100	A
84 - 89	AB
78 - 83	B
72 - 77	BC
66 - 71	C
60 - 65	D
<60	F

Note: The instructor reserves the right to increase the final scores for the class as a whole at his discretion.

Homework

There will be homework to be assigned regularly during the semester. Homework may include a variety of activities including mathematical derivations, problem sets, and computer programming.

All homework assignments will be posted in Canvas. The due date and instructions will be provided in the assignments. All handwritten homework solutions should be neat, legible, and well organized.

Note: Late homework will NOT be accepted. Homework with the lowest score will be dropped.

Exams

There will be two in-class, open-book, midterm exams. If you have a valid schedule conflict, please arrange for a make-up exam at least one week prior to the scheduled exam. There will be no accommodations made for last-minute requests.

Final Project

A project will be used to assess your understanding of the course material. Students may work individually or in teams of two. The goal of the project is to implement the control methods learned in the course on a robotic system, either in simulation or hardware. A project proposal will be due in mid-March. After reviewing your proposal, I will provide feedback and confirm whether you may proceed. Each team will give a project presentation in late April and submit a final report in early May. For two-person teams, both members will receive the same grade.

Textbook & Software

Textbook

There is no required textbook. The following materials are available for reference:

1. Numerical Optimization of Dynamic Systems, Moritz Diehl and Sebastien Gros, 2016.
[<https://www.syscop.de/files/2015ws/noc-dae/00-book.pdf>]
2. Feedback Systems - An Introduction for Scientists and Engineers, Karl Johan Astrom and Richard M. Murray, Princeton University Press, 2009.
[https://www.cds.caltech.edu/~murray/books/AM08/pdf/am08-complete_22Feb09.pdf]
3. R. Siegwart, I. R. Nourbakhsh, D. Scaramuzza. Introduction to Autonomous Mobile Robots. MIT Press, 2nd Edition, 2011.
4. H. Khalil, Nonlinear Systems, 3rd Edition, Prentice Hall Publisher, 2002.
5. Jessy W. Grizzle, Mathematics for Robotics, University of Michigan.
[<https://github.com/michiganrobotics/rob501>]
6. Russ Tedrake, Underactuated robotics: Learning, planning, and control for efficient and agile machines course notes for MIT 6.832, MIT.
[<https://underactuated.csail.mit.edu/index.html>]

Software

MATLAB and Simulink software are required. There are four ways to access the software:

1. [recommended] Download and install in the local computer via [Campus Software Library](#). Instructions for download and installation can be found here: <https://kb.wisc.edu/page.php?id=82710>. Select the latest version. Simulink and MATLAB toolboxes will be installed as part of the standard installation package.
2. Remote access with [XenApp](#) and [VPN](#)
3. Online at the [Mathworks website](#). You must create an account using your UW-Madison email
4. Use any computer in a [CAE Lab](#)

We will use Casadi (<https://web.casadi.org/>) for solving optimization and optimal control problems.

Additional Course Information and Academic Policies

Academic Integrity Statement

By virtue of enrollment, each student agrees to uphold the high academic standards of the University of Wisconsin-Madison; academic misconduct is behavior that negatively impacts the integrity of the institution. Cheating, fabrication, plagiarism, unauthorized collaboration, and helping others commit these previously listed acts are examples of misconduct which may result in disciplinary action. Examples of [disciplinary action](#) include, but is not limited to, failure on the assignment/course, written reprimand, disciplinary probation, suspension, or expulsion.

Common examples of academic misconduct include:

- cheating on an examination
- contrary to the stated rules of the course
- submitting a paper or assignment as one's own work when a part or all of the paper or assignment is the work of another
- submitting a paper or assignment that contains ideas or research of others without appropriately identifying the sources of those ideas
- stealing examinations or course materials
- submitting, if contrary to the rules of a course, work previously presented in another course
- tampering with the laboratory experiment or computer program of another student
- knowingly and intentionally assisting another student in any of the above, including assistance in an arrangement whereby any work, classroom performance, examination or other activity is submitted or performed by a person other than the student under whose name the work is submitted or performed

Course Evaluation

Students at the University of Wisconsin–Madison have the opportunity to evaluate their learning experiences and the courses they are enrolled in through course evaluations. Many instructors use a digital course evaluation tool to collect feedback from students. Student participation is an integral component of course development, and confidential feedback is important. UW–Madison strongly encourages student participation in course evaluations.

Accommodations for Students with Disabilities

The University of Wisconsin–Madison supports the right of all enrolled students to a full and equal educational opportunity. The Americans with Disabilities Act (ADA), Wisconsin State Statute (36.12) and UW–Madison policy ([UW-855](#)) require the university to provide reasonable accommodations to students with disabilities to access and participate in its academic programs and educational services. Faculty and students share responsibility in the accommodation process. Students are expected to inform faculty of their need for instructional accommodations during the beginning of the semester, or as soon as possible after being approved for accommodations. Faculty will work either directly with the student or in coordination with the [McBurney Disability Resource Center](#) to provide reasonable instructional and course-related accommodations. Disability information, including instructional accommodations as part of a student's educational record, is confidential and protected under FERPA.

Tentative Schedule

Module	Week	Date	Topics	Logistics
Control Fundamentals	1	1/21 (W)	Course introduction	HW1
	2	1/26 (M)	State-space modeling	HW2
		1/28 (W)	Linearized model	
	3	2/2 (M)	Lyapunov stability	HW3
		2/4 (W)	Lyapunov direct method	
	4	2/9 (M)	Finding Lyapunov function via SOS	HW4
		2/11 (W)	Lyapunov indirect method	
	5	2/16 (M)	Controllability	HW5
		2/18 (W)	Stabilizability	
Exam 1	6	2/23 (M)	Midterm Exam 1	
Numerical Optimal Control		2/25 (W)	Optimization Basics	
	7	3/2 (M)	KKT Conditions	HW6
		3/4 (W)	HJB Method	
	8	3/9 (M)	Infinite-time LQR	HW7
		3/11 (W)	Finite-time LQR	
	9	3/16 (M)	Direct Methods	HW8
		3/18 (W)	Pontryagin Minimum Principle w/o Input Constraints	
	10	3/23 (M)	Pontryagin Minimum Principle w/ Input Constraints	HW9
		3/25 (W)	Model Predictive Control	
Spring Break	11	3/30 (M)	No Class (Spring Recess)	
		4/1 (W)	No Class (Spring Recess)	
Exam 2	12	4/6 (M)	Midterm Exam 2	
Quadcopter Planning & Control		4/8 (W)	Quadcopter kinematics & dynamics	
	13	4/13 (M)	Quadcopter state estimation	HW10
		4/15 (W)	Differential flatness	
	14	4/20 (M)	Quadcopter control & motion planning	HW11
4/22 (W)		Quadcopter simulation & experiment		
Project	15	4/27 (M)	Final Project Presentation	
		4/29 (W)	Final Project Presentation	Final Report

The exact schedule may change at the discretion of the instructor.