COURSE INFORMATION

Prerequisites: ME 240 or ROB 215 or equivalent.

Textbook: None required. Materials and notes will be posted on Canvas. Recommended textbooks (available online through the UM library) are listed under *Additional References*.

Attendance Policy: In-person attendance (for both lectures and recitation sessions) is strongly encouraged but not required. If you must miss class for any reason, recordings will be available under the *Lecture Recordings* section on Canvas within 24 hours of the lecture. Regardless of attendance, you are responsible for the content of both lectures and recitation.

Course Description

Feedback control design and analysis with emphasis on robotics applications, including linear (e.g., independent joint) and nonlinear (e.g., coupled joints) systems. Classical control theory topics include linearization, time response, stability, Routh–Hurwitz stability analysis, transfer functions, poles and zeros, root locus, frequency response, Bode plots, gain and phase margins, and lead/lag/PID control. State-space topics include state transition matrix, multivariable robot control, linear quadratic optimal control, and observers.

Course Learning Objectives

1. Teach the students the basic concepts of automatic control.
2. Introduce time-domain and frequency-domain system analysis techniques based on linear models.
3. Introduce feedback control design methods and their application to control of robotic systems (both linear and nonlinear).
4. Familiarize students with relevant MATLAB software tools.

Assignments & Exams

1. Homework

There will be homework due approximately every other week. Exact due dates will be solidified later in the semester.

Homework is generally due at 11:59 pm on the due date and will be submitted to Gradescope (accessible through Canvas). You are responsible for ensuring that you have uploaded all files properly and on time. The submission site will remain open for 15 minutes past the nominal deadline to accommodate last-minute technological issues. Past that grace period you will not be able to submit, but everyone gets one dropped assignment.

The total number of points for each homework set may vary based on the number of assigned problems. When computing homework averages, each set will be normalized to 100% and your lowest score will be dropped. If you have a concern with your homework grading, please contact the GSI first. The instructor will only get involved after you have given the GSI a chance to address the concern.

You are encouraged to discuss homework with fellow students at the conceptual level, but you must complete all calculations and write-up, from scratch to final form, on your own. Verbatim copying of another student's work is forbidden. You are not permitted to consult homework solutions from previous terms and courses.

Hints: Start early. Work on problems as material is covered in lecture and discussion. Extensions are granted only in exceptional circumstances. Study the lecture notes and review recordings (if helpful) before starting. Many problems require synthesis of concepts taught up to that point in the semester.

Graduate section (ROB 599): There will be an additional assignment at the end of class. This specific assignment is *not* eligible for the dropped-grade policy. If you do not submit it, you will receive a zero.

2. Midterm Exam

Thursday, October 30 (in class).

3. Final Exam

Monday, December 15, 10:30 am–12:30 pm (set by the Registrar).

Grade Distribution

Homework	30%
Midterm Exam	35%
Final Exam	35%

Piazza

Piazza (accessible through Canvas) facilitates Q&A and peer discussions. Rather than emailing the teaching staff, please post your questions on Piazza (except when related to grades). Check if your question has already been answered before posting. You are encouraged to contribute to answers—the more you help, the more others will help you. Instructors and GSIs will regularly check the site, but do *not* expect immediate responses (especially late at night before deadlines). Please refrain from discussing exact homework solutions prior to their due date.

Additional References (Textbooks and Software)

Suggested (not required) textbooks, accessible from the UM Library:

[1] Hassan Khalil, *Control Systems: An Introduction*, 2023.

[2] Mark W. Spong, Seth Hutchinson, and M. Vidyasagar, *Robot Modeling and Control*, 2020.

[3] Karl Johan Aström and Richard M. Murray, *Feedback Systems: An Introduction for Scientists and Engineers*, 2008.

[4] *Control Tutorials for MATLAB and Simulink*.

University of Michigan College of Engineering Honor Code

All students are presumed to be decent and honorable, and all are bound by the College of Engineering Honor Code. You may not seek unfair advantage over fellow students; you may not consult, look at, or possess the unpublished work of another without permission; and you must appropriately acknowledge your use of another's work. Any violation of the honor policies will be reported to the Honor Council.

For more information about the Standards of Conduct, Honor Code, and the Statement of Student Rights and Responsibilities, see: https://bulletin.engin.umich.edu/rules/.

Disability Statement

The University of Michigan is committed to providing equal opportunity for participation in all programs, services, and activities. Requests for accommodations may be made by contacting the Services for Students with Disabilities (SSD) Office (G664 Haven Hall, phone: 734-763-3000). Once eligibility is determined, you will be issued a verified individual services accommodation (VISA) form. Please present this form at the beginning of the term, or at least two weeks prior to the need for the accommodation.

Inclusion Statement

It is our intention that students from all backgrounds and perspectives will be well served by this course, and that the diversity students bring will be viewed as an asset. We welcome individuals of all ages, backgrounds, beliefs, ethnicities, genders, gender identities, gender expressions, national origins, religious affiliations, sexual orientations, socioeconomic backgrounds, family education levels, and abilities—as well as other visible and nonvisible differences. All members of this class are expected to contribute to a respectful, welcoming, and inclusive environment. Suggestions are encouraged and appreciated.

Detailed Course Outline

Lecture 01: Introduction to Control, Feedforward Control, and Basic Feedback Loop
Lecture 02: State-Space Models
Recitation: Math Preliminary
Lecture 03: Equilibria and Linearization
Lecture 04: Time Response of Linear Systems (Due to Initial Conditions)
Recitation: MATLAB Basics (Symbolic Math Toolbox, `ode45`)
Lecture 05: Time Response of Linear Systems (Due to Constant Input) and Standard Form of 2nd-Order Systems
Lecture 06: Standard Form of 2nd-Order Systems (Continued) and Control Requirements

Recitation: Feedback Linearization, State-Transition Matrix & Eigenvalues
Lecture 07: Stability and Routh–Hurwitz Criterion
Lecture 08: PD Control / PID Intro
Recitation: MATLAB Control System Toolbox, Lyapunov Stability
Lecture 09: PID Control / Independent Joint Modeling and Control
Lecture 10: Multivariable Control
Recitation: Complex Numbers, Laplace Transform Review
Lecture 11: Transfer Functions (Laplace Transform, Poles and Zeros)
Lecture 12: Transfer Functions (Steady-State Output to Constant/Periodic Input, Model Interconnections, Final Value Theorem, Case Study up to Block Diagram)
Recitation: Block Diagram Simplification, Simulink Tutorial, Mason's Gain Formula (Tentative)
Lecture 13: Transfer Functions (Case Study Continuation) / Root Locus – Introduction [Instructor out of town]
Lecture 14: Root Locus – PD and PID
Recitation: Drawing Rules for Root Locus
Fall Break
Lecture 15: Flexible Joint Robot and Pole–Zero Cancellation Introduction
Recitation: TBD
Lecture 16: Pole–Zero Cancellation (Continuation) – Case Study: Speeding up System Response with PID
Lecture 17: Lead Compensator, Frequency Response – Introduction, First-Order Filter
Recitation: Midterm Review
Lecture 18: Frequency Response – Butterworth Filter and Bode Plots
Lecture 19: Midterm [Instructor out of town]
Recitation: Zeros, Filters
Lecture 20: Frequency Response – Bandwidth and Stability Criterion
Lecture 21: Frequency Response – Gain and Phase Margin
Recitation: Bode Plot Drawing Rules
Lecture 22: Frequency Response – Proportional Control Design via Bode Plots; Intro to Lag
Lecture 23: Lag Compensator, Lead Compensator
Recitation: Lead–Lag Compensator Design Examples
Lecture 24: PID Control Design and Intro to LQR
Lecture 25: Advanced Topics: LQR (Stabilization) and Intro to LQI (Command Tracking)
Recitation: Optimization and Model Predictive Control
Lecture 26: Advanced Topics: LQI (Command Tracking) Continued and LQE (Kalman Filter)
Thanksgiving Break
Lecture 27: Advanced Topics: Digital Implementation and MPC
Lecture 28: Review
Recitation: Review

Homework Sets (Topics)

Homework 1

- Basic feedforward and feedback loop (simple computations)
- Deriving the Segway model in state space
- Computing equilibria of the Segway model

- Linearization about upright equilibrium
- Simulating system response

Homework 2

- Designing stabilizing controllers (PD and PID) in state space with Routh–Hurwitz
- Tuning system response

Homework 3

- Nonlinear control of planar RR robot
- Model uncertainty

Homework 4

- SEA control with both motor and load angle feedback
- State-space representation and transfer functions
- Routh–Hurwitz and root locus stability
- Modeling with Simulink and simulation

Homework 5

- Actuator frequency response example
- Convert TF from Vel/Torque to Pos/Torque
- Derive closed-loop Bode plot with PD control around position

Homework 6

- LQR control of series elastic actuator (flexible joint robot)
- LQE observer of mass–spring–damper