SE 5202: Modern Control Systems

Course Instructor: Abhishek Dutta, Ph.D.

Catalog Description. 3 credits. This course is a modern take on control design and analysis and uses state-space and optimization-based approaches to deal with complex cyberphysical systems. The course builds on the necessary classical control systems analysis techniques in the frequency domain, but moves quickly to the more advanced time-domain optimization-based control and estimator design. The course includes both practical and theoretical aspects. The control design of cyberphysical systems is challenging as together with inadequate measurements and stringent performance criteria, they are often multivariable, nonlinear and uncertain in nature. The multivariable state-space based optimal control design and estimation techniques presented in this course teach students how to obtain maximum system performance with imprecise measurements. Students learn to design and analyze nonlinear and robust controllers, which apply to a wide range of ubiquitous systems affected by nonlinearity and perturbations. A full nonlinear model of a B747 aircraft is introduced as an advanced cyberphysical system and throughout the course practical controllers are developed for both the longitudinal and lateral flight dynamics that correspond to material covered. Students use Matlab-based controller code for the B747 aircraft example, amongst others, that they simulate to obtain hands-on training and in-depth understanding of modern control systems.

Pre-Requisites. An undergraduate degree in engineering or science and knowledge of basic control systems.

Intended Audience. The course is designed for all graduate students in engineering.

Course Delivery Method. The course will be offered online, asynchronously, in small recorded modules according to the course syllabus. Direct and live communication with the instructor will be available once a week for discussion, questions and quizzes.

Anticipated Student Outcomes. By the end of the course, students can

1. Understand control system design, implementation and verification.
2. Understand usefulness, appropriate applications, impediments and obstacles in control design.
3. Formulate and interpret control requirements and recognize the elements of a control system.
4. Create systems models for control and analyze their subsequent response.
5. Design linear control systems considering fundamental limits and contrast with nonlinear control synthesis.
6. Design classical controls based on root locus and bode plots and understand practical implementation issues.
7. Characterize stability and uncertainty of systems and construct a robust controller.
8. Apply modern state-space oriented methods from multivariable modeling to control.
9. Determine the need of estimation and its association with the controller.
10. Construct and integrate optimization-based estimators and controllers.
11. Conduct basic model-in-the-loop based testing, verification, validation and tuning.

Course Organization. The course is organized into five learning modules: (1) System Modeling, Characteristics and Response, (2) Control Design and Analysis in Frequency Domain, (3) Control Design and Analysis in State-Space, (4) Control Synthesis involving State Estimation, and (5) Control Synthesis for Nonlinear and Uncertain Systems. Structuring of these 5 learning modules into 14 lectures of a one-semester course, along with the topics and references, is included below.

Course Outline

------------ Learning Module I: System Modeling, Characteristics and Response----------

Objectives: This module introduces the objective and various components of a control system and the subsequent construction of its block diagram. System modeling using transfer functions and state-space representation and response of second order systems are covered next. The following questions are answered: what are state-space models and how are they developed, how are they related to control design, what are the basic properties and how does one analyze these? Linearization technique is demonstrated over the modeling of a full aircraft. The transformations between transfer functions and state-space concludes the module.

Lecture 1: Introduction

- Goal of control system.
- Elements of control system.
- Basic linear system modeling and response.

Lecture 2: Properties of State-space Models

- State-space representation of physical systems.
- Equilibrium points and linearization of nonlinear system.
- Stability of LTI system.
- Linearization of full nonlinear aircraft dynamics and other examples with code.
- Transfer function to state-space model.
- State-space models to transfer function.
- State-space transformations.

-------------Learning Module II: Control Design and Analysis in Frequency Domain-----

Objectives: This module reviews the frequency response based classical control methods and builds a working knowledge of the same. An aircraft control example is used to illustrate the principles of root locus: start, end, locus of points and asymptotes. The proportional-integral derivative controller is introduced and the final value theorem is used to compute the tracking errors. Controller synthesis using root locus and pole placement are presented. Next, analysis, synthesis, performance and stability of a system using frequency response methods are dealt with. Specifically, the Nyquist criterion for stability and Bode plots for sketching are emphasized. Bode's gain phase relationship is used as a tool for frequency domain design. Finally, the lead and lag controllers are covered together with adequate example code.

Lecture 3: Root Locus Analysis

- Aircraft longitudinal dynamics autopilot design.
- Root locus basics: analysis and synthesis of closed loop control.
- Tracking various commands.
- Dynamic compensation based controller synthesis.
- RL design using Matlab.

Lecture 4: Frequency Response Methods

- Frequency response as complementary to root locus methods.

- Frequency response function and sketching approximation.
- Frequency based stability tests.
- Gain and phase margins.
- Nyquist stability theorem with examples.

Lecture 5: Control Design Using Bode Plots

- Bode's gain phase relationship.
- Error response.
- Second order system performance.
- Frequency domain design: lead mechanics and lag compensation.
- Lead and lag design Matlab examples with code.

------------Learning Module III: Control Design and Analysis in State-Space-------------

Objectives: This module extensively deals with the modern state-space based design methods. First, the circumstances under which a state-space model can be observed and controlled to any arbitrary trajectory are presented and extended to weaker conditions on the same. These questions are answered: how does one select the closed-loop pole locations and then how does one change the pole locations together with example code. Tracking arbitrary references is discussed. Optimization based full state feedback control with the linear quadratic regulator is introduced followed by ways to formulate the cost function and solving the resulting optimization.

Lecture 6: State-space Features: Observability and Controllability

- Zeros and transfer function matrices.
- Formal definition of observability and unobservable state.
- Formal definition of controllability and uncontrollable state.
- Modal tests and example.
- Weaker conditions: detectable and stabilizable.

Lecture 7: Full-state Feedback Control

- Full-state feedback controller design with example.
- Design insights using controllability.
- Ackermann's pole-placement formula.
- Reference input tracking with example.
- Pole-placement example with full Matlab code.

Lecture 8: Linear Quadratic Regulator

- LQR formulation and weight matrix selection.
- Algebraic Riccati Equation and constrained optimization.
- Aircraft lateral dynamics LQR with Matlab code.
- DOFB LQ with examples and code.
- LQR stability margins.

----------------Learning Module IV: Control Synthesis involving State Estimation-------

Objectives: This module deals with the practical case where the thus far assumed full state information is not available and how to best estimate using available measurements. Where to put the estimator poles is addressed. The compensator is introduced as the combination of estimator with regulator with a simple example, code and plots. The case with arbitrary references is discussed. An optimal estimator for linear system is developed as a dual of the optimal regulator. Finally, the optimal estimator and regulator are combined to design linear quadratic Gaussian.

Lecture 9: Open-loop and Closed-loop Estimators

- Estimation schemes: open-loop and closed-loop.
- Estimator gain selection.
- Dual design approach.
- Observer example with code examples.

Lecture 10: Combined Estimators and Regulators

- Compare and combine estimators and regulators.
- Separation principle.
- Dynamic output feedback compensator.
- Simple compensator and dynamic output feedback examples with code.
- Aircraft control design examples with code.
- Compensator for tracking reference inputs with multiple examples.

Lecture 11: Linear Quadratic Estimator and Gaussian

- Steady-state optimal estimator.
- LQE as dual of LQR.
- Combination of optimal estimator and regulator.
- LQG robustness.

Objectives: This module deals with advanced but pragmatic topics on robustness to uncertainty, treatment of nonlinear systems and digital control implementation. Limits on performance leading to bounded gain are touched upon. What happens if model of the system is incorrect is answered by starting off with modeling uncertainty. Mechanics to visualize robustness are developed. Robust performance as a combination of nominal performance and robust stability is covered next, all in the frequency domain. Multi-in multi-out response is analyzed followed by singular value decomposition, followed by simple design example. Discrete controls for computer implementation with code layout are presented. Nonlinear systems are analyzed next, along with limit cycle behavior using describing functions and example code. A very general method to test stability of nonlinear systems based on Lyapunov and invariance concludes the course.

Lecture 12: Closed-loop System Analysis

- SISO design approaches.
- Bounded gain theorem.
- Model uncertainty.
- Robust stability.
- Nominal performance.
- Robust performance.

Lecture 13: Multivariable and Digital Control Basics

- Multivariable frequency response with code.
- H-infinity synthesis with code.
- Sample and hold analysis.
- Computer code layout.

Lecture 14: Analysis of Nonlinear Systems

- Describing Function Analysis.
- Saturation and odd nonlinearities.
- Limit cycle analysis.
- Lyapunov stability theorem with several examples.
- LaSalles's invariance principle.
- Differential flatness.

USEFUL READING

Texts are available through a local or online bookstore. The UConn Co-op carries many materials that can be shipped via its online Textbooks To Go service. For more information, see Textbooks and Materials on our Enrolled Students page.

Primary Course Textbook

Franklin, Gene, J. David Powell, and Abbas Emami-Naeini. *Feedback Control of Dynamic Systems*. 6th ed. Prentice Hall, 2009. ISBN: 9780136019695.

Copyright. Copyrighted materials within the course are only for the use of students enrolled in the course for purposes associated with this course and may not be retained or further disseminated.

Grading. During the semester, students will be challenged in four areas that are designed to help them to successfully realize proficiency in the student outcomes: Participation, Homework, Oral Presentations, and Project Report. The final course grade will be based on the following:

- Homework: Optional
- Design Projects (Mid-term): 30%
- Design Projects (End-term): 40%
- Paper Presentation on Design Project: 30%

Project-work. A project is to be developed by each student, which is expected to evolve during the entirety of the course. The final deliverable (paper presentation) should identify the elements introduced in the course in a quantifiable manner and suggest a strategy for solution. All assignments will be posted on HuskyCT along with due dates and graded subsequently. Required materials should be submitted via HuskyCT.

Software. This course will make extensive use of Matlab and Simulink software.

Student Conduct: http://www.dosa.uconn.edu/student_code.html. You are responsible for acting in accordance with the University of Connecticut's Student Code Review and become familiar with these expectations. In particular, make sure you have read the section that applies to you on Academic Integrity:

- Academic Integrity in Graduate Education and Research

Cheating and plagiarism are taken very seriously at the University of Connecticut. As a student, it is your responsibility to avoid plagiarism. If you need more information about the subject of plagiarism, use the following resources:

- Plagiarism: How to Recognize it and How to Avoid It
- Instructional Module about Plagiarism
- University of Connecticut Libraries' Student Instruction (includes research, citing and writing resources)

Attendance. Attendance will not be taken; however, it is practically impossible to follow the class if classes are missed.

Absences. Make-up of missed exams requires permission from the Dean of Students, see "Academic Regulations." Midterm-exams are treated the same as Final Examinations. Students involved in official University activities that conflict with class time must inform the instructor in writing prior to the anticipated absence and take the initiative to make up missed work in a timely fashion. In addition, students who will miss class for a religious observance must "inform their instructor in writing within the first three weeks of the semester, and prior to the anticipated absence, and should take the initiative to work out with the instructor a schedule for making up missed work."

Adding or Dropping a Course. If you should decide to add or drop a course, there are official procedures to follow:

- Matriculated students should add or drop a course through the Student Administration System.
- Non-degree students should refer to Non-Degree Add/Drop Information located on the registrar's website.

You must officially drop a course to avoid receiving an "F" on your permanent transcript. Simply discontinuing class or informing the instructor you want to drop does not constitute an official drop of the course. For more information, refer to the online Graduate Catalog,

Academic Calendar. The University's Academic Calendar contains important semester dates.

Students with Disabilities.

Students needing special accommodations should work with the University's Center for Students with Disabilities (CSD). You may contact CSD by calling (860) 486-2020 or by emailing csd@uconn.edu. If your request for accommodation is approved, CSD will send an accommodation letter directly to your instructor(s) so that special arrangements can be made. (Note: Student requests for accommodation must be filed each semester.)

Course Schedule*

Week 1	*Lecture 1: Introduction*
Week 2	*Lecture 2: Properties of State-space Models*
Week 3	*Lecture 3: Root Locus Analysis*
Week 4	*Lecture 4: Frequency Response Methods*
Week 5	*Lecture 5: Control Design Using Bode Plots*
Week 6	*Lecture 6: State-space Features: Observability and Controllability*
Week 7	*Lecture 7: Full-state Feedback Control*
Week 8	*Lecture 8: Linear Quadratic Regulator*
Week 9	*Lecture 9: Open-loop and Closed-loop Estimators*
Week 10	*Lecture 10: Combine Estimators and Regulators*
Week 11	*Lecture 11: Linear Quadratic Estimator and Gaussian*
Week 12	*Lecture 12: Closed-loop System Analysis*
Week 13	*Lecture 13: Multivariable and Digital Control Basics*
Week 14	*Lecture 14: Analysis of Nonlinear Systems*

Helpful links:

- Virtual Computer Lab at UConn: http://skybox.uconn.edu/
- Course Material: https://lms.uconn.edu
- Institute for Advanced Systems Engineering: http://www.utc-iase.uconn.edu/