USC Viterbi School of Engineering

EE593, Robust Multivariable Control

Units: 04
Primary audience: MS and PhD students
Term: Fall
Day: Tu, Th
Time: 5:00-6:50 pm

Note: This course has been upgraded to a 4-unit course. This coming fall will be the first time it is taught in the 4-unit format. Note that, contrary to undergraduate classes, we are following the traditional schedule https://viterbigrad.usc.edu/ starting Aug 24. The last day of class still needs to be confirmed. Because of the uncertain situation with COVID-19, things might still change; therefore, please, check the blackboard on a regular basis.

Location: Class was initially supposed to be "hybrid," with SLH 100 reserved, but because of the worsening COVID-19 situation, it will most likely be "online."

Instructor: E. Jonckheere
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Office: EEB306
Office Hours: Tu & Th 2:00-4:00 pm (probably through Skype)
Contact Info: jonckhee@usc.edu (expect reply to email within 48 hours) or Skype: edmond.jonckheere

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IT Help: Distance Education Network (DEN)
Hours of Service:
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(213)740-9356

Course Description

Review of various robust multivariable control architectures (classical versus modern, centralized, decentralized, networked, etc). Sensitivity and complementary sensitivity matrices; uncertainty representation; singular values Bode plots. Multivariable Nyquist stability criterion. Structured uncertainties, structured singular values, and Bode plots of structured singular values. Fundamental limitations in achievable performance; Bode integral limitations. Nevanlanna Pick interpolation, Nehari extension, Hankel operators, and contractive dilation approaches to internal stability and fundamental limitations. Parameterization of stabilizing controllers. Algebraic Riccati Equations. Linear Quadratic regulator, Bounded Real Lemma approach to modern H-infinity design. Notion of cooperatiove versus noncooperative games. Adverserial game approach to modern H-infinity design.

Theoretical concepts will be put into practice by a benchamark space structure example that would serve as culmination of the class. Other cutting edge applications that could be considered include power grid and quantum communication control (depending on students' interests.)

This is a course "beyond the basics," for on-campus students eager to get into the deeper conceptual foundations of control and for those students from industry in need of learning the modern control design methods.

Learning Objectives

Students will be able to design controllers for many-input, many-output sytems with guaranteed robustness against model uncertainty. In addition, students will become acquainted with the mathematical principles (e.g., complex function theory, Principle of Optimality, Game theory) behind the practical design methods.

Prerequisite(s): EE482 (Linear Control Systems) and EE585 (Linear System Theory)

Co-Requisite(s): EE585 (Linear System Theory). While it is preferred that the student has already taken EE585 before embarking in EE593, taking EE585 concurrently is acceptable.

Concurrent Enrollment: N/A

Knowledge of Nonlinear & Adaptive Control on the level of EE587 is recommended but not required.

Course Notes

Grading Type: letter grade

The course will most probably be "online," through **webex.**

Copies of lecture slides and other class information will be posted on Blackboard.

Classroom utilization of **Matlab and Mathematica** will be used as multimedia/technology-enhanced learning strategies.

Technological Proficiency and Hardware/Software Required

Students will be assumed to be familiar with Matlab. However, this class also involves polynomial matrix manipulations for which Mathematica is best. Students will be asked to install Mathematica on their computer and a "crash course" in Mathematica will be given.

Required Readings and Supplementary Materials

Required textbook: Kemin Zhou and John C. Doyle, "Essentials of Robust Control." Prentice Hall, Upper Saddle River, NJ, 1998. ISBN 0-13-525833-2.

Additional recommended text: Sigurd Skogestad and Ian Postlethwaite, "Multivariable Feedback Control: Analysis and Design," 2nd Edition, Wiley, Nov. 2005, ISBN: 978-0-470-01167-6.

Additional (required) reading:

- [PAJ] Ian R. Petersen, Brian D.O. Anderson and Edmond A. Jonckheere, ``A first principles solution to the nonsingular control problem," *International Journal on Robust and Nonlinear Control,* vol. 1, pp. 171-185, 1991.
- [SJVL] M. G. Safonov, E. A. Jonckheere , M. Verma, D. J. N. Limebeer, "Synthesis Of Positive Real Multivariable Feedback Systems," *International Journal of Control,* Vol. 45, Issue 3, pp. 817-842, 1987.
- [WJ] Bing-Fei Wu and Edmond A. Jonckheere, "A simplified approach to Bode's theorem for continuous-time and discrete-time systems", *IEEE Transactions on Automatic Control,* volume AC-37, number 11, pp. 1797-1802, November, 1992.

Required textbook will be available through the USC bookstore. Additional recommended text can be obtained through Amazon (https://www.amazon.com/Multivariable-Feedback-Control-Analysis-Design/dp/0470011688/ref=asc_df_0470011688/?tag=hyprod-20&linkCode=df0&hvadid=266179548166&hvpos=1o1&hvnetw=g&hvrand=10587077444440463224&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=&hvtargid=pla-453711516850&psc=1) or Barnes & Noble (https://www.barnesandnoble.com/p/multivariable-feedback-control-sigurd-skogestad/1101200631/2662170539643?st=PLA&sid=BNB_ADL+Marketplace+Good+Used+Textbooks+-+Desktop+Low&sourceId=PLAGoNA&dpid=tdtve346c&2sid=Google_c&gclid=EAIaIQobChMIu_PHrNyP5QIV6R-tBh0VSgboEAQYAiABEgLvXvD_BwE). The additional readings will be made available through the blackboard.

Description and Assessment of Assignments

Students will be assigned a homework every other week. Homework will consist in solving textbook problems and will include a "research-oriented" problem to probe and stimulate students' creativity. There will be one midterm and one final.

Grading Breakdown

Assignment	Points	% of Grade
participation		5%
homework		20%
midterm		35%
final		40%
TOTAL	0	1

Grading Scale (Example)

Course final grades will be determined using the following scale (subject to "curving.")

A	90-100
A-	80-90
B+	75-80
B	70-75
B-	65-70
C+	63-65
C	60-63
C-	58-60
D+	55-58
D	53-55
D-	50-53
F	50 and below

Assignment Rubrics

N/A

Assignment Submission Policy

Homework assigned on Tuesday (or first day of class of the week), to be submitted two weeks after assignment, same day of the week.
Late assignments will be penalized (10%), unless valid reason, e.g., medical problem, family or other emergency

Grading Timeline

Graded homework are expected to be returned within one week.

Additional Policies

Attendance of the lectures is expected.
Matlab and Mathematica will be used in the classroom.
Cellphones are to be turned off before beginning of class.

Course Schedule: A Weekly Breakdown

	Topics/Daily Activities	Readings and Homework	Deliverable/ Due Dates
Week 1, starting Aug. 24	Various **architectures** of control systems (classical, modern, centralized, decentralized, networked). Concepts of feedback performance, uncertainty and robustness. Classical applications: Space structures & Modern applications: Power grid & Quantum communication & Transmission Control Protocol (TCP) applications	Zhou-Doyle, Chapter 1	
Week 2, starting Aug. 31	Review of linear algebra & systems. Matrix inversion lemma and application to modern architecture for structured uncertainties, singular values, controllability, observability, realization, interconnected systems	Zhou-Doyle, Chapters 2, 3	Homework #1 assigned
Week 3, starting Sept. 7	Closed-loop (internal) stability; multivariable Nyquist stability criterion; uncertainty modeling; review of classical gain & phase margins and multivariable extensions; Bode singular value plots of sensitivity and complementary sensitivity matrices; structured singular values in both cases of complex and real perturbations, complex-analytic theory of μ-function, application of Carathéodory boundary behavior of conformal maps, structured singular values plots and its applications to quantum control.	Zhou-Doyle, Sections 2.6, 6.1-6.3, Chapters 5, 8	
Week 4	Fundamental limitations	Zhou-Doyle, Sections 6.4,	Homework #1 due,

starting Sept. 14	on achievable feedback performance. Bode integral limitations via multivalued function theory. Illustration on the "inverted pendulum on a cart" as a model of human gait.	6.5	Homework#2 assigned.
Week 5, starting Sept. 21	Frobenius norm; elementary parametric design; notion of power spectral density; H-two versus H-infinity design		
Week 6, starting Sept. 28	Algebraic foundation of multivariable theory: Smith-McMillan form; multivariable poles/zeros; notion of rational coprime factorization; Bezout identity; crash course in MATHEMATICA	Handout provided by instructor	Homework #2 due, Homework #3 assigned
Week 7, starting Oct. 05	Historical development of H-infinity; Nevanlinna – Pick interpolation; all-pass property; Nehari extension, Hankel operators, Sarason's contractive dilation, parameterization of all stabilizing controllers; Q-parameter solution to H-2 and H-infinity problems.	Zhou-Doyle, Section 5.4. Zhou-Doyle, Chapter 11.	
Week 8, starting Oct. 12	Bellamn's Principle of Optimality; the linear-quadratic regulator problem	Zhou-Doyle, Chapter 13	Homework #3 due Midterm week
Week 9, starting Oct. 19	Algebraic Riccati equation and its computational solutions	Zhou-Doyle, Chapter 13	
Week 10, starting Oct 26	Bounded real lemma; positive realness and circuit theory interpretation; dissipation as hysteresis in stress-strain diagram, in space structures. Introduction to smart materials.	Notes provided by instructor [SJVL]; Zhou-Doyle Example 4.2, Section 12.4	**Homework #4 assigned**
Week 11, starting Nov. 02	Bounded real lemma approach to H-infinity design	Notes provided by instructor [SJVL]; Zhou-Doyle Example 4.2, Section	

		12.4	
Week 12, starting Nov. 09	Notion of adversarial game: application to control and filtering. Generalization of the concept of cooperatice versus noncooperative games in stochastic setting. Witsenhausen conjecture, Nash equilibrium.	Zhou-Doyle, Chapter 14	Homework # 4 due Homework #5 assigned
Week 13, starting Nov. 16	Game theoretic/separation approach to 2-Riccati equation solution to H-infinity**.**	Zhou-Doyle, Chapter 14	
Week 14, starting Nov. 23	Various "loop-shifting" techniques to relax conditions for 2-Riccati equation solutions to H-infinity to be applicable. Grand space structure example as culmination of class.	Zhou-Doyle, Chapter 14	Last day of class: Tu, November 24; homework #5 due on that day.
Week 15, starting Nov. 30			"Personal study week"
FINAL			Date: Dec. 03, 2020, 4:30-6:30 pm. Please consult the USC *Schedule of Classes* at https://viterbigrad.usc.edu/

Midterm and final are sit-down, open books & open notes exams with laptops to solve design problems.

Statement on Academic Conduct and Support Systems

Academic Conduct:
Plagiarism – presenting someone else's ideas as your own, either verbatim or recast in your own words – is a serious academic offense with serious consequences. Please familiarize yourself with the discussion of plagiarism in *SCampus* in Part B, Section 11, "Behavior Violating University Standards" https://policy.usc.edu/scampus-part-b/. Other forms of academic dishonesty are equally unacceptable. See additional information in SCampus and university policies on scientific misconduct, http://policy.usc.edu/scientific-misconduct.

Support Systems:
Counseling and Mental Health - (213) 740-9355 – 24/7 on call
studenthealth.usc.edu/counseling/
Free and confidential mental health treatment for students, including short-term psychotherapy, group counseling, stress fitness workshops, and crisis intervention.

National Suicide Prevention Lifeline - 1 (800) 273-8255 - 24/7 on call
http://www.suicidepreventionlifeline.org
Free and confidential emotional support to people in suicidal crisis or emotional distress 24 hours a day, 7 days a week.

Relationship and Sexual Violence Prevention Services (RSVP) - (213) 740-9355(WELL), press "0" after hours - 24/7 on call
https://studenthealth.usc.edu/sexual-assault/
Free and confidential therapy services, workshops, and training for situations related to gender-based harm.

Office of Equity and Diversity (OED) - (213) 740-5086/Title IX - (213) 821-8298
https://equity.usc.edu/, http://titleix.usc.edu/
Information about how to get help or help someone affected by harassment or discrimination, rights of protected classes, reporting options, and additional resources for students, faculty, staff, visitors, and applicants.

Reporting Incidents of Bias or Harassment - (213) 740-5086 or (213) 821-8298
https://usc-advocate.symplicity.com/care_report/
Avenue to report incidents of bias, hate crimes, and microaggressions to the Office of Equity and Diversity |Title IX for appropriate investigation, supportive measures, and response.

The Office of Disability Services and Programs - (213) 740-0776
http://dsp.usc.edu
Support and accommodations for students with disabilities. Services include assistance in providing readers/notetakers/interpreters, special accommodations for test taking needs, assistance with architectural barriers, assistive technology, and support for individual needs.

USC Campus Support and Intervention - (213) 821-4710
https://uscsa.usc.edu/
Assists students and families in resolving complex personal, financial, and academic issues adversely affecting their success as a student.

Diversity at USC - (213) 740-2101
https://diversity.usc.edu/
Information on events, programs and training, the Provost's Diversity and Inclusion Council, Diversity Liaisons for each academic school, chronology, participation, and various resources for students.

USC Emergency - UPC: (213) 740-4321, HSC: (323) 442-1000 – 24/7 on call
http://dps.usc.edu/, http://emergency.usc.edu
Emergency assistance and avenue to report a crime. Latest updates regarding safety, including ways in which instruction will be continued if an officially declared emergency makes travel to campus infeasible.

USC Department of Public Safety - UPC: (213) 740-6000, HSC: (323) 442-1200 – 24/7 on call
http://dps.usc.edu
Non-emergency assistance or information.