University of Illinois at Urbana Champaign
Department of Aerospace Engineering
Spring 2021

AE 555: Multivariable Control Design

4 credit hours

This syllabus is not an exhaustive description of all details of the course; the students are free to contact the instructor with any additional questions or concerns at any time.

Instructor

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Office: 319H Talbot
Office hours: whenever
Contact: most easily by e-mail, as in-person communication might be limited during the semester

Lecture Times and Organization

While all sections of this syllabus are subject to change given the fluid COVID-19 situation, this section is particularly fluid. To the best of the instructor's knowledge and desires, lectures will generally be held in *403B2 Engineering Hall* on *TR 2:30-3:50pm*. They will be video-taped and accessible to all students almost immediately after the lecture; the lecture classroom is subject to capacity restrictions, but will likely be able to seat at least some of the students, if not all, who are interested in participating in-person. If there is interest, online group office hours and review sessions will be organized as needed. Temporary or permanent adjustments to this plan, or to the schedule of classes, are possible and likely. Attendance is *not* mandatory – students are welcome to adjust their course experience to their learning style, as long as doing so does not disturb learning styles of the others.

Course Description

AE 555 builds on introductory control courses, which nearly all consider linear systems, possibly with only a single input and a single output, by saying "*But most of the systems are nonlinear, have multiple inputs, and multiple outputs*". In such scenarios, many of the previously established notions, and resulting mathematical theories, fall flat on their face. We do not know how to verify whether a nonlinear system is controllable. An asymptotically stable system does not necessarily converge exponentially to an equilibrium point. The input-output relationship becomes difficult to characterize.

To some extent, the theory of linear systems can be extended to nonlinear ones, and analogous results can be obtained, often at a significant increase in mathematical effort. Sometimes we have no answers to seemingly simple questions. The purpose of AE 555 is to expose the listener both to the rich, elegant, and exciting mathematical structure of nonlinear control systems and to the limits of our knowledge about nonlinear systems. In a sense, in addition to proving results that enable (partially) successful analysis of nonlinear systems, the course provides at least a partial answer as to why undergraduate control courses are almost invariably focused on linear systems. To do both these tasks, the course introduces a wealth of theoretical notions – e.g., vector fields, different notions of stability, limit sets, invariant sets – and uses them to derive a variety of mathematically beautiful results on the behavior of nonlinear systems. The course particularly focuses on theoretical topics central to control of aerospace systems: (i) invariance, stability, and controllability – basic building blocks in control design for multivariable systems, (ii) methods to approximate and simplify the behavior of a nonlinear system, and (iii) control design for with a priori partially unknown systems. By the end of the course, students will gain familiarity with the fundamental notions and limitations of nonlinear control, as well as with basic methods to design control laws for nonlinear systems. The course will be mathematically rigorous, and will – as an additional "soft skill" – insist on developing the students' capability for writing and understanding formal mathematical proofs.

Assignments and Grading

The deliverables for the course will consist of 6 homework assignments and a final exam. The weights for the deliverables will be distributed as follows:

Homework 1: 5%
Homework 2: 10%
Homework 3: 10%
Homework 4: 10%
Homework 5: 15%
Homework 6: 15%
Final exam: 35%

Additional extra credit may be offered during the semester, but should not be counted on.

While students are encouraged to consult additional literature, all deliverables will largely follow the material covered in the lectures.

The final grades for the course will be calculated by the following formula: A-/A/A+ = 90-100, B-/B/B+ = 80-89.99, C- /C/C+ = 70-79.99, D-/D/D+ = 60-69.99, F = 0-59.99, where the "-" modifier will be assigned to those grades with the unit digit 0-1 (e.g., 91.87 = A-) and "+" modifier to those grades with the unit digit 8-9 (e.g., 78.02 = C+). The grades will not be rounded up, rounded down, nor "curved".

Form and Submission of Deliverables

Written submissions of the homework assignments will be due at **noon** (Central time) of the deadline dates indicated by the instructor (see tentative course outline for predicted dates). Late submission of a particular deliverable, if not agreed with the instructor, will be penalized at the rate of 15% of the weight of the deliverable per day (prorated for the actual delay time; e.g., a 2-hour delay incurs a penalty of 1.25% of the total value of the deliverable).

Assignments should be submitted to the course Compass 2g page. Students are responsible for timely submission of the assignments. If there are issues with the page, students are welcome to submit the assignments to the instructor by e-mail.

Given the current COVID-19 situation, the final exam will likely be in a “take-home+” format, where students will have three days to complete a long exam, and will then discuss their answers in person (over Zoom) with the instructor, which might cause a change in the final exam mark. The oral part of the exam is not intended to comprehensively cover all of the course material, but simply result in a broader discussion on the problems that the student had seen and solved already.

Emergencies do happen; when faced with unavoidable obstacles – and such obstacles will almost certainly arise given the current state of flux of the society – students should contact the instructor for any modifications to the deliverable schedules.

Prerequisites and Literature

There is no required text for the course. With possible small exceptions intended for independent study, all new topics required for success in the course will be discussed during the lectures. This course is a fairly advanced control class; ECE 515 / ME 540 is an official prerequisite. With faith in the student’s sense of self-assessment and responsibility, the prerequisite can be waived to the maximal extent allowed, but strong knowledge of linear state-space control is needed (which usually goes beyond the undergraduate-level introductory control courses).

The course material will mainly follow *Nonlinear Systems* by Hassan Khalil, which can be found in the university library, including online. While this textbook will be useful for the course, the material covered in the course will not cover everything in the book, and there may be elements of the course not found in the book. The course deliverables will not explicitly refer to the book at any point. *Students are not required to purchase any textbooks or other materials.*

Academic Integrity

Students are welcome to work together on their homework assignments, and use any literature available to them. They are, however, required to:

1) write submissions on their own,
2) mention any peers they were working and any online or offline sources that they used, and
3) respond to any subsequent questions on the material posed by the instructor, whether in person or over e-mail. The answers to the instructor’s questions may affect the assigned mark.

Because of the nature of the final exam, students are expected to work alone on it, while making use of literature. In the oral element of the final exam the instructor will ask questions to establish the student’s familiarity with the submitted answers.

Students are required to familiarize themselves with the University’s Academic Integrity Policy and Procedure, available at http://studentcode.illinois.edu/article1/part4/1-401/, and abide by that policy in full.

Accommodations

To obtain disability-related academic adjustments and/or auxiliary aids, students that require special accommodations must contact the instructor and the Disability Resources and Educational Services (DRES) as soon as possible. Students are welcome to contact the instructor at any time with any accommodation-related needs. To contact DRES, visit 1207 S. Oak St., Champaign, call 217-333-4603 (V/TTY), e-mail a message to disability@illinois.edu, or visit https://www.disability.illinois.edu. If a student is concerned that they have a disability-related condition that is impacting their academic progress, there are academic screening appointments available that can help diagnosis a previously undiagnosed disability. These may be accessed by visiting the DRES website.

Illinois law requires the University to reasonably accommodate its students' religious beliefs, observances, and practices in regard to admissions, class attendance, and the scheduling of examinations and work requirements. If there is a conflict between course deadlines and any religious observances, students should notify their instructor as soon as they realize the conflict.

Privacy and Reporting

The University of Illinois is committed to combating sexual misconduct. Faculty and staff members are required to report any instances of sexual misconduct to the University's Title IX Office. In turn, an individual with the Title IX Office will provide information about rights and options, including accommodations, support services, the campus disciplinary process, and law enforcement options. A list of the designated University employees who, as counselors, confidential advisors, and medical professionals, do not have this reporting responsibility and can maintain confidentiality, can be found here: https://wecare.illinois.edu/resources/students. Other information about resources and reporting is available here: https://wecare.illinois.edu.

Any student who has suppressed their directory information pursuant to Family Educational Rights and Privacy Act (FERPA) should self-identify to the instructor to ensure protection of the privacy of their attendance in this course. See https://registrar.illinois.edu/academic-records/ferpa/ for more information on FERPA.

Campus Emergency Plan

The university's emergency response recommendations can be found at the following website: http://police.illinois.edu/emergency-preparedness/. Students should review this website and the appropriate campus building floor plans website within the first 10 days of class: http://police.illinois.edu/emergency-preparedness/building-emergency-action-plans/.

Modifications to the Syllabus

The instructor reserves the right to modify any and all parts of this syllabus throughout the semester. All modifications will be made solely in the interest of time scheduling, beneficial adaptation to changing public health circumstances, accurate measurement of the students' success, and improvement of the students' educational outcomes. Any modifications will be transparently communicated to the students.

Tentative Course Outline

Week	Topic	Tuesday	Thursday
1: Jan 25-29	Introduction to nonlinear systems; vector fields and dynamical systems	Regular class	Regular class
2: Feb 1-5	Existence and uniqueness of solutions, dependence on initial conditions, comparison principles	Regular class	Regular class **Homework 1 given**
3: Feb 8-12	Invariance; Bony-Brezis theorem	Regular class	Regular class **Homework 1 deadline**
4: Feb 15-19	Stability	Regular class	Regular class **Homework 2 given**
5: Feb 22-26	Lyapunov theory	Regular class	Regular class **Homework 2 deadline**
6: Mar 1-5	Lyapunov theory	Regular class	Regular class **Homework 3 given**
7: Mar 8-12	Aerospace examples	Regular class	Regular class **Homework 3 deadline**
8: Mar 15-19	LaSalle invariance principle	Regular class	Regular class **Homework 4 given**
9: Mar 22-26	Feedback linearization	Regular class	Regular class **Homework 4 deadline**
10: Mar 29 – Apr 2	Feedback linearization	Regular class	Regular class **Homework 5 given**
11: Apr 5-9	Small-time local controllability	Regular class	Regular class **Homework 5 deadline**
12: Apr 12-16	Small gain theory	No class	Regular class
13: Apr 19-23	Adaptive control	Regular class	Regular class **Homework 6 given**
14: Apr 26-30	Adaptive control	Regular class	Regular class **Homework 6 deadline**
15: May 3-7	Aerospace examples	Regular class	No class
-- : May 10-14	**Final exam given: Monday, May 10** **Final exam written deadline: Thursday, May 13** **Oral discussion: Thursday, May 13 and Friday, May 14**		