Fall 2016
EE 587
Nonlinear and Adaptive Control
Dr. E. Jonckheere

<u>Note:</u> This coming Fall 2016 semester, this course will be taught in a way that makes sense to both Electrical Engineering (EE) and Aerospace & Mechanical Engineering (AME) students. By special EE-AME arrangement, AME students are welcome to take this EE587 course and should be able to get AME credit for it. Furthermore, the control courses across the Viterbi School of Engineering (VSoE) are going through a major restructuration involving course consolidation, modernization, cross-listing, etc. While EE587 and AME 552 will remain as they are and will be cross listed, a new *Differential Geometric Nonlinear Control* course will be developed. This EE587 version will somehow be a first step towards that goal. This major restructuration of control courses across the VSoE might be a little confusing to the students, but Dr. Jonckheere will be available for clarification and advisement if necessary.

Synopsis

The purpose of this course is to expose graduate students to the *fundamental principles* of nonlinear systems and controls, including a taste of adaptive techniques. Both state-space and input/output techniques will be developed conjointly. Instead of emphasizing nonlinear stability (e.g., Popov and circle criteria), as traditional nonlinear science has done over the past 40 years, here, the emphasis will rather be on such more design-oriented concepts as *tracking and disturbance rejection*. As such, the traditional describing function will be de-emphasized in favor of the more modern differential geometric methods. The basic "surviving skills" in Lie groups and Lie algebras to tackle contemporary problems (e.g, quantum control) will be developed. The physically motivated Lagrangian control will also be introduced as a convenient way to deal with robotics and electromechanical problems.

Although EE587 is not a research class, a course in nonlinear system theory is a gateway to cutting edge topics. As we are currently witnessing the emergence of quantum control as a source of new control paradigms, it is fitting to offer some introduction to this topic, especially since quantum control belongs to the class of bilinear control problems—probably the only class of nonlinear problems that have complete analytical solutions in

terms of matrix algebra. Traditionally, bilinear control is the problem of controlling systems like

$$\dot{x} = Ax + (Bx)u,$$

which offer an excellent example of a (tractable!) Lie bracket control problem. It is not hard to see that the above bilinear system is a formalization of the Schrödinger equation

$$i\hbar \frac{\partial \psi(q,t)}{\partial t} = \left(H_0\left(-i\hbar \frac{\partial}{\partial q}, q \right) + V(q)u \right) \psi(q,t)$$

with control input u that acts as the intensity of the perturbation with potential $V(q)$.

But probably the most important quantum control problem is to shield a quantum information system from the environmental bath, which has the effect of destroying coherence. This problem is formulated with the density operator

$$\rho = \Sigma_i p_i |\psi_i\rangle\langle\psi_i|$$

where the wave function $|\psi_i\rangle$ has probability p_i and the off-diagonal terms of ρ are the coherences to be protected from the environment. The dynamics of the density is modeled by the Lindblad-Liouville-von Neumann equation (written in a system of units where $\hbar = 1$):

$$\frac{\partial \rho}{\partial t} = -i[H_0 + H_u u, \rho] + L(\varphi)\gamma$$

where H_0 is the free Hamiltonian, $H_u u$ is the control Hamiltonian, and $L(\rho)\gamma$ is the interaction with the environment. The problem of isolating the qubits from the environment will be approach as the rejection of the disturbance γ. The link with this course is that the problem can be reformulated in the bilinear state space format

$$\dot{x} = Ax + (Bx)u + (Gx)\gamma$$

Instructor:

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Meeting time & place:

Tue, Thu, 5:00-6:20 p.m., OHE 120.

Office hours (instructor):

Tue, Thu, 1:30-3:30 p.m.

Grader:

TBA

Teaching Assistant :

TBA

Textbook:

H. K. Khalil, *Nonlinear Systems*, Third Edition, Prentice Hall, 2002. ISBN: 0-13-067389-7. This is an excellent text, very much aligned with the way EE587 has been taught over the past few years, up to today's standards, a bit "cut and dry," but the lectures notes will supplement the text with real-life examples.

Supplemental (recommended) texts:

- Romeo Ortega, Antonio Loria, Per Johan Nicklasson, and Hebertt Sira-Ramirez, Passivity Based Control of Euler-Lagrange Systems, Springer, 1998. ISBN: 1-85233-016-3. A very good book on physically motivated Lagrangian control.
- Jean-Jacques Slotine and Weiping Li, *Applied Nonlinear Control*, Prentice Hall, 1991. ISBN: 0-13-040890. This used to be the nominal textbook over the past few years, but this text has become outdated; moreover, it is not quite up to the recent developments in the field. A big problem with that text is that the coverage of the input-output approach to nonlinear stability is grossly inadequate. But the strength of this book is that it is physically motivated, has plenty of real life examples, many pictures of elementary nonlinear systems, many examples, etc. It is definitely a good supplemental reading.
- J. L. Casti, *Nonlinear System Theory*, Academic Press, 1985. ISBN 0-12-163452-3. (An old book, but still up to date, dealing with such advanced topics as chaos, catastrophes, nonlinear realization theory. The topics covered are truly outstanding problems but a little too far fetched for such a course as ee587.)
- D. Elliott, *Bilinear Systems*, Springer, 2009. An excellent reference for bilinear systems written by an expert in the field. The main point of this book is that, even though bilinear systems are "nonlinear," they are amenable to linear algebra techniques.
- V. V. Nemytskii and V. V. Stepanov, *Qualitative Theory of Differential Equations,* Dover, New York, 1989. A superb book covering very well the first topic of the class (fundamental facts, Poincare index, etc.) https://www.amazon.com/Qualitative-Theory-Differential-Equations-Mathematics/dp/0486659542
- W. Hurewicz, *Lectures on Ordinary Differential Equations,* Dover, 2014. Another superb book, at the level of this EE587 class, readable by EE587 students, but written by one of the greatest mathematicians of all times. https://www.amazon.com/Lectures-Ordinary-Differential-Equations-Mathematics/dp/0486664201

Homework:

One homework every other week, assigned on Tue., due on Tue two weeks after assignment.

Exams:

- One midterm (TBA)
- One final

Prerequisites:

Basic linear feedback control (EE482); good working knowledge of linear algebra (EE441); Linear System Theory (EE585) is not a "must," but is desirable as a "recommended preparation."

Weight:

Homework	15%
Midterm	35%
Final	50%
Total	100%

Course Schedule:

Topics	Chapters in Khalil	Chapters in Ortega et al.	Time table
Fundamental facts about nonlinear systems: phase space, equilibrium points, elementary topological methods (Poincare index), graphical methods (isoclines), and elementary limit cycle theory (Poincaré theory).	1, 2, 3, Appendix B		August-September 2016
Lyapunov theory.	4		September 2016
Input/Output stability analysis: Hilbert and Banach spaces of signals, passivity and small gain concepts, the circle criterion, the off-axis circle criterion, and the Popov criterion.	5,6,7	A	October 2016
Differential geometric control: manifolds, Lie groups, Lie algebras, Lie brackets, nonlinear controllability, linearization method, nonlinear tracking, nonlinear disturbance rejection. Quantum control as an application of control of bilinear systems.	12,13		October-November 2016
Lagrangian and Hamiltonian	14.4	1, 2, 3, D	November 2016

methods: Lagrange, Euler, and Hamilton equations of motion, Lagrangian control and related dissipativity concepts, with application to robot control and electrodynamics. Lagrangian systems as yet another example bilinear control.			
Adaptive systems: Elementary adaptation concepts.	4.2		December 2016

The first four topics (*fundamental facts, Lyapunov stability, Input-Output, and especially Differential geometry*) will be covered in detail. The last two topics (*Lagrangian and adaptive controls*) will only be quickly surveyed, and we might have to make some choices, depending on how far we will have gone and students' interests.

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 Section 11, *Behavior Violating University Standards*https://scampus.usc.edu/1100-behavior-violating-university-standards-and-appropriate-sanctions/. 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/.

Discrimination, sexual assault, and harassment are not tolerated by the university. You are encouraged to report any incidents to the *Office of Equity and Diversity* http://equity.usc.edu/ or to the *Department of Public Safety* http://capsnet.usc.edu/department/department-public-safety/online-forms/contact-us. This is important for the safety whole USC community. Another member of the university community – such as a friend, classmate, advisor, or faculty member – can help initiate the report, or can initiate the report on behalf of another person. *The Center for Women and Men* http://www.usc.edu/student-affairs/cwm/ provides 24/7 confidential support, and the sexual assault resource center webpage sarc@usc.edu describes reporting options and other resources.

Support Systems

A number of USC's schools provide support for students who need help with scholarly writing. Check with your advisor or program staff to find out more. Students whose primary language is not English should check with the *American Language Institute* http://dornsife.usc.edu/ali, which sponsors courses and workshops specifically for international graduate students. *The Office of Disability Services and Programs* http://sait.usc.edu/academicsupport/centerprograms/dsp/home_index.htmlprovides certification for students with disabilities and helps arrange the relevant accommodations. If an officially declared emergency makes travel to campus infeasible, *USC Emergency Information* http://emergency.usc.edu/will provide safety and other updates, including ways in which instruction will be continued by means of blackboard, teleconferencing, and other technology.