Spring 2013
EE 587
Nonlinear and Adaptive Control

(Note: This course is offered sequentially in each of its version: The version taught by Dr. Jonckheere emphasizes differential geometry control, while the version taught by Dr. Ioannou emphasizes adaptive control)

Dr. E. Jonckheere

The purpose of this course is to expose beginning 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, as traditional nonlinear science has done over the past 30 years, here, the emphasis will rather be on such more design-oriented concepts as *tracking and disturbance rejection*. As such, the traditional describing function approach 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:

Wd., 6:30-9:20 p.m., KAP 145.

Office hours:

TBA

Grader:

TBA

Teaching assistant (if applicable)

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.

Homework:

One homework per week, assigned on Wd., due the following Wd.

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		January 2013
Lyapunov theory.	4		Jan.-Feb. 2013
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	February 2013
Differential geometric control: manifolds, Lie groups, Lie algebras, Lie brackets, nonlinear controllability, linearization method, nonlinear tracking. Quantum control as an application of control of bilinear systems.	12,13		March-April 2013
Lagrangian and Hamiltonian methods: Lagrange, Euler, and Hamilton equations of motion, Lagrangian control and related dissipativity concepts, with application to robot control and electrodynamics.	14.4	1, 2, 3, D	April 2013
Adaptive systems: Elementary adaptation concepts.	4.2		April 2013

The first four topics (*fundamental facts*, *Lyapunov stability*, *Input-Output*, *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.