ENEE 661: Nonlinear Control Systems (Tu-Th 2:00-3:15 pm, spring 2011, CSI 3120)
Course website http://www.enee.umd.edu/courses/enee661.S2011/

Instructor: P. S. Krishnaprasad (krishna@isr.umd.edu; 301-405-6843); office in A.V. Williams Building - room 2233. Office hours: M 4:00-6:00 and Tu 5:10 -7:00.

Course Goals: This is a *significantly revised* version of the core course in nonlinear control systems. It is aimed to provide an introduction to Lie-algebraic and analytic methods for the *qualitative* behavior of nonlinear systems, and the synthesis and design of controllers for such systems. Using Lie brackets and physical examples (e.g. pumping a swing, unicycle kinematics, forced rigid body, switched electrical circuits, robot motion planning), concepts such as controllability, equilibria, periodic orbits, stability, stabilization, passivity, and steady-state response of input-output systems will be discussed. Techniques include Lyapunov's direct method, Chetaev's instability theorem, linearization, frequency domain stability analysis, and functional analytic methods. Techniques with a geometric flavor, including center manifold reduction, feedback linearization, and elementary bifurcation analysis will be introduced. We will also discuss briefly nonlinear oscillations and averaging theory. Examples from physics, engineering and biology will be used throughout the course.

Course Prerequisite: ENEE 660 (see http://www.ece.umd.edu/class/enee660.F2010/) or equivalent, or permission of instructor. A prior course in advanced calculus (e.g. MATH 410 or MATH 411) is recommended. A good course in differential equations would also serve as adequate mathematics background.
Topic Prerequisite: It is desirable that the student be familiar with basic concepts and tools from linear system theory including, the matrix exponentials and the variation of constants formula, controllability, observability and stabilizability, and the Nyquist criterion. It would be helpful (but not essential) to be familiar with normed vector spaces, the Inverse Function Theorem, and the Implicit Function Theorem. We will cover these items. The discussion of Lie algebras and Lie groups will be self-contained and no algebraic background is assumed beyond linear algebra and what is used in ENEE 660.

References:
(a) H. K. Khalil, *Nonlinear Systems,* Prentice Hall, 3rd ed., Englewood Cliffs, 2002 (**this is the textbook**);
(b) S. Sastry, *Nonlinear Systems: Analysis, Stability and Control*, Springer-Verlag (series in interdisciplinary applied mathematics), New York, 1999;
(c) M. Vidyasagar, *Nonlinear Systems Analysis,* 2nd ed., Prentice Hall, Englewood Cliffs, 1993;
For mathematical background on advanced calculus, we **highly** recommend:
(d) A. Avez, *Differential Calculus,* Springer-Verlag, New York, 1986;
For background material on frequency domain methods in linear systems, see:
(e) G. F. Franklin, J. D. Powell and A. Emami-Naeini, *Feedback Control of Dynamic Systems,* 2nd edition, Addison-Wesley, Reading, 1991;
For background material on linear systems, **see ENEE 660 website** noted above and/or
(f) T. Kailath, *Linear Systems*, Prentice Hall, Englewood Cliffs, 1980;
(g) W. J. Rugh, *Linear System Theory,* Prentice Hall, Englewood Cliffs, 1993.

Core Topics:

1. Vector fields, Lie brackets and controllability.
2. Existence, uniqueness and continuous dependence on initial conditions of solutions to ordinary differential equations.
3. Lyapunov's direct method for time-invariant and time-varying systems; stability and instability results of Lyapunov and Chetaev; Lasalle's Invariance Principle.
4. Regions of attraction and their estimation, matrix Lyapunov equation.
5. Linearization Theorem, stability and instability results.
6. Passivity, input-output stability and the Small Gain Theorem.
7. Passivity and absolute stability (Circle and Popov criteria).
8. Stabilization using state feedback (via linearization), and input-output linearization.
9. Periodic orbits and orbital stability.

Additional Topics (a selection from) Nonlinear observability, and invertibility; Volterra series representation and realization theory; relative degree and zero dynamics; bifurcations; perturbation theory and averaging; singular perturbations; nonlinear dynamics of algorithms for optimization; models of hysteresis; applications in robotics, network flow control, cooperative control, spacecraft dynamics, adaptive control and evolutionary games.

Grading: Weekly homework sets (10%), Mid-term Examination I on **Thursday, February 24** (25%), Mid-term Examination II on **Thursday, April 7** (25%), and Final Examination (40%) to be held in **two parts –** in class, **Monday May 16, 10:30 a.m. – 12:30 p.m**., and **take home** the same evening for a maximum of 5 hours of work. The mid-terms and the in-class part of the final examination will be of the **closed-book** variety. (Do not make travel plans to leave before May 18.)

Policy on Collaboration and Classroom Environment:

(a) Students are encouraged to discuss problems in groups. **But all written submitted work should be individual in nature.**

(b) It is of utmost importance to maintain a classroom environment conducive to focus on and attention to instruction. **Hence usage of electronic devices (music equipment, cell phones, text messaging devices and computers) is disallowed during regular class hours.**