ENEE 661: Nonlinear Control Systems (M W 5:00-6:15 pm, spring 2020, AJC 2121)
Course website http://www.enee.umd.edu/courses/enee661.S2020/ with Lecture Notes (pdf). **Instructor**: P. S. Krishnaprasad (krishna@isr.umd.edu; 301-405-6843); office in A.V. Williams Building - room 2233. Office hours: Tue 5:00 – 7:00 pm (planned for optional discussion session), and additional hours TBD.

Course Goals: This is a core course on nonlinear control systems. It aims to provide an introduction to analytic, geometric, and Lie-algebraic methods to understand the behavior of nonlinear systems, and the synthesis and design of controllers for such systems. Using physical examples (pumping a swing, unicycle kinematics, forced rigid body, robot motion planning, bipedal locomotion, switched electrical circuits etc.), concepts such as Lie brackets, controllability, equilibria, periodic orbits, stability, stabilization, passivity, and steady-state response of input-output systems will be discussed. Analytical methods covered include Lyapunov's direct method, Chetaev's instability theorem, linearization and Lyapunov's indirect method, frequency domain stability analysis, and theorems on function spaces. Methods with a geometric flavor, including center manifold reduction, feedback linearization, and elementary bifurcation analysis will be introduced. We will also touch briefly on the subject of nonlinear oscillations and averaging principles. 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/ at least (lectures 1(a)-3(b) and Problem Sets 1-3)) or equivalent, or permission of instructor. A 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, 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** see http://www.egr.msu.edu/~khalil/NonlinearSystems/)
(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, SIAM 2002
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** (above) and
(f) R. W. Brockett, *Finite Dimensional Linear Systems*, Wiley 1970, SIAM 2015
(g) T. Kailath, *Linear Systems*, Prentice Hall, Englewood Cliffs, 1980

Core Topics:

1. Vector fields, Lie brackets and controllability.
2. Integrating *a single vector field* – Cauchy-Lipschitz Theorem: Existence, uniqueness and continuous dependence on initial conditions of solutions to ordinary differential equations. Integrating *a set of vector fields* – Clebsch-Deahna-Frobenius theorem
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 and associated 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, human movement, spacecraft dynamics, adaptive control and evolutionary games. Nonsymmetric Riccati equations as flows on Grassmann manifolds

Grading: Weekly homework sets (10%), Mid-term Examination I (Monday, March 2) (25%), Mid-term Examination II (Wednesday, April 15) (25%), and Final Examination (Monday, May 18, 4:00 – 6:00) (40%). All exams are of closed book variety.

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 disruptive electronic devices (music equipment, cell phones, text messaging devices and laptop computers) is disallowed during regular class hours.** Students seeking to use tablet computers for note-taking should ask for permission.