University of Waterloo
Department of Electrical & Computer Engineering
ECE 688: Nonlinear Systems

Winter 2019

Lecture times, building and room number: Monday 11:30pm to 2:20pm; EIT 3141.

Instructor: Prof. Christopher Nielsen.
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Office hours: By appointment.
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Course description: Why should one study nonlinear systems? Virtually all physical systems are nonlinear in nature. Sometimes it is possible to describe the operation of a physical system by a linear model. This is the case, for example, if the mode of operation of the system does not deviate too much from the "nominal" set of operating conditions. But in analyzing the behaviour of any physical system, one often encounters situations where the linearized model is inadequate or inaccurate. That is the time that the material covered in this course may prove useful.

In this course we cover classical and modern approaches to the analysis of finite-dimensional, deterministic, nonlinear systems modeled by ordinary differential equations with an emphasis on stability, robustness and the effect of interconnecting dynamical systems. The material in this course may appeal to engineers interested in a rigorous treatment of nonlinear systems and finds applications in all branches of engineering.

Recommended background: ECE 380 (or equivalent) and familiarity with basic calculus.

Textbook

There is no required text for this course. Instructor will provide electronic course notes and write on the board. An excellent **optional** textbook is

Nonlinear Systems, 3rd edition, H.K. Khalil.

Additional references

- Nonlinear Systems Analysis, 2nd edition, M. Vidyasagar.
- Nonlinear Control Systems II, A. Isidori.
- $\mathcal{L}_2$-Gain and Passivity Techniques in Nonlinear Control, A. van der Schaft.

Evaluation

50% Final exam: open book.

35% Assignments: Four (4) assignments spread over the term.

5% Tutorials: Schedule to be determined.

10% Course project.

Tentative Topics

1. **Introduction to nonlinear models and phenomena**
   Examples.

2. **Mathematical preliminaries**
   Functions, Norms, topology of $\mathbb{R}^n$, continuity on $\mathbb{R}^n$, differentiability on $\mathbb{R}^n$.

3. **The vocabulary of dynamical systems**
   Phase and integral curves, phase portraits, state transition function, phase flows, vector fields, existence and uniqueness of solutions, equilibria, closed orbits, invariant sets and limit sets.

4. **Lyapunov stability**
   Autonomous systems, invariance principle, sign definite functions, domain of attraction, linearization, converse theorems, stability and small perturbations.

5. **Input-output models**
   "$\mathcal{L}$ spaces" and their extensions, input-output maps, small gain theorem, linear systems with nonlinear feedback.

6. **Input-to-state stability**
   Cascade connected systems, feedback connected systems, small gain theorem for ISS systems.

7. **Dissipative systems**
   Definitions, relationship with Lyapunov stability, classes of dissipative systems, control affine systems with quadratic supply rates, linear systems, absolute stability problem.

8. **Introduction to output regulation**
   Centre-manifold theory, tracking for nonlinear control systems (local theory), single-input single-output control affine systems with relative degree.

Academic integrity, grievance, discipline, appeals and note for students with disabilities: see www.uwaterloo.ca/accountability/documents/courseoutlinestmts.pdf. The text on that web site is listed below.

Academic integrity: In order to maintain a culture of academic integrity, members of the University of Waterloo community are expected to promote honesty, trust, fairness, respect and responsibility. [Check www.uwaterloo.ca/academicintegrity/ for more information.]

Grievance: A student who believes that a decision affecting some aspect of his/her university life has been unfair or unreasonable may have grounds for initiating a grievance. Read Policy 70, Student Petitions and Grievances, Section 4, www.adm.uwaterloo.ca/infosec/Policies/policy70.htm. When in doubt please be certain to contact the department's administrative assistant who will provide further assistance.

Discipline: A student is expected to know what constitutes academic integrity [check www.uwaterloo.ca/academicintegrity/] to avoid committing an academic offence, and to take responsibility for his/her actions. A student who is unsure whether an action constitutes an offence, or who needs help in learning how to avoid offences (e.g., plagiarism, cheating) or about "rules" for group work/collaboration should seek guidance from the course instructor, academic advisor, or the undergraduate Associate Dean. For information on categories of offences and types of penalties, students should refer to Policy 71, Student Discipline, www.adm.uwaterloo.ca/infosec/Policies/policy71.htm. For typical penalties check Guidelines for the Assessment of Penalties, www.adm.uwaterloo.ca/infosec/guidelines/penaltyguidelines.htm.

Appeals: A decision made or penalty imposed under Policy 70 (Student Petitions and Grievances) (other than a petition) or Policy 71 (Student Discipline) may be appealed if there is a ground. A student who believes he/she has a ground for an appeal should refer to Policy 72 (Student Appeals) www.adm.uwaterloo.ca/infosec/Policies/policy72.htm.

Note for students with disabilities: The Office for persons with Disabilities (OPD), located in Needles Hall, Room 1132, collaborates with all academic departments to arrange appropriate accommodations for students with disabilities without compromising the academic integrity of the curriculum. If you require academic accommodations to lessen the impact of your disability, please register with the OPD at the beginning of each academic term.