EE 588
Linear-Quadratic Control
Dr. E. Jonckheere
Spring 2012

The purpose of this course is to develop the basic tools and techniques of linear-quadratic optimization in both the *control* context (the Linear-Quadratic-Gaussian problem also referred to as LQG problem) and the *estimation* context (the Kalman-Bucy filtering problem). The most natural approach to such problems is via modern state-space techniques and, as such, this course can be viewed as a spinoff of EE585, *Linear Systems Theory*.

However, linear-quadratic optimization also has such traditional feedback interpretations as disturbance rejection, Bode limitation, phase and gain margins, etc., which were overlooked for a while before Horowitz, Zames, Rosenbrock, and many others reemphasized the importance of traditional control concepts against the then prevailing modern state-space/stochastic techniques. In this course, we will strive to develop jointly the modern and the traditional aspects in some kind of symbiotic theory. This aspect of the course is very well covered by the textbook by Dorato et al. If time allows, and depending on students' interests, we might develop a quick introduction to H^∞ design.

Proceeding further, the Linear-Quadratic-Gaussian (LQG) problem will be viewed as an entry to the field of stochastic control. Having been somewhat ignored for many years, *stochastic control is currently experiencing a revival*, because of many recent applications that are either fundamentally stochastic (e.g., quantum mechanics) or applications that strive to optimize systems under the presence of random disturbances. Such applications include Internet control (e.g., congestion notification is fundamentally stochastic and requires the definition of a "stochastic differential equation driven by a Poisson process"), smart grid (where topology faults make the system hybrid/stochastic), quantum control (e.g., stochastic decoherence rate), even financial engineering (sustainability of the volatility, heteroskedasticity, Black–Scholes equation etc.) All of these new applications call for a deeper understanding of stochastic processes. In this context, it is fitting to go over the Ito versus Stratonovich stochastic calculus pitfall. Cutting edge applications will be chosen, depending on students' interests, among Random Early Detection (RED) in network control, Active Queue Management (AQM), video streaming, the Kushner-Stratonovich equation of quantum control through scheduling of measurements, the continuous measurement equations in quantum control, or the Black-Scholes formula.

Prerequisites:

EE482, *"Linear Control Systems,"* and EE585, *"Linear Systems Theory,"* are *recommended preparations* rather than formal prerequisites. Of course, the students will be expected to be familiar with basic feedback theory (stability, gain/phase margins, Bode diagrams, etc.) and state space theory (state space equation, controllability, observability). An understanding of the fundamental concepts of random variables is necessary, but EE562a, "*Random Processes in Engineering*" is *not* a prerequisites. The fundamental *survival* concepts of random processes necessary for this course will be reviewed. By the same token, we will try to eradicate the Ito versus Stratonovich calculus confusion, which has plagued the development of stochastic control. Thus, except for this foundational material, we will try to make the course as self-contained as possible.

Instructor:

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Office hours:

Mo. & Wd. 2:00-4:00 p.m.

Meeting time & place:

6:35-9:20 p.m., Wd.; KAP 140

Grader:

TBA

Textbook:

- P. Dorato, C. Abdallah, and V. Cerone, *Linear-Quadratic Control—An Introduction,* Prentice Hall, 1995, ISBN: 0-02-329962-2. This is a *very terse and concise* monograph covering the most important aspects of linear-quadratic optimization and its traditional feedback interpretation. Those students finding it a bit too short are invited to look at the "supplemental texts." Besides, the textbook will be supplemented by notes on advanced topics (e.g., Internet & quantum control) posted on the blackboard.

Supplemental (recommended) texts:

- H. Kwakernaak and R. Sivan, *Linear Optimal Control Systems,* Wiley-Interscience, 1972, ISBN: 0-471-51110-2. This book is a little old, is missing latest developments, but it has remained a "classic" and should be easy to read for graduate students.
- B. D. O. Anderson and J. B. Moore, *Optimal Control—Linear-Quadratic Methods*, Prentice-Hall Information and System Science Series, 1990, ISBN: 0-

13-638560-5. This book covers the state-space theory as well as its traditional feedback interpretations fairly well. It should not be too hard to read for graduate students. It contains some good aerospace examples of linear-quadratic optimization.

- V. Ionescu, C. Oara, and M. Weiss, *Generalized Riccati Theory and Robust Control*, Wiley, 1999, ISBN: 0-471-97147-2. This is probably the best book of its kind, but it is definitely beyond the scope of EE588. But it could be of interest to students planning to pursue a Ph.D. thesis on linear-quadratic optimization and related techniques.

Homework:

One homework every other week, assigned on Wd., due Wd.

Exams:

- One midterm: Wd., March 07, 2012. (I put the midterm right before Spring recess, as my experience tells me that this is what students prefer—like that, students can go on their Spring break without the hassle of having to think about a midterm during vacation.)
- One final: the official schedule of final examinations states:
  "6 or any class after 6 p.m. meeting once weekly
  7-9 p.m. first scheduled class period, May 2-9"
  This places the final examination on May 02, 7:00-9:00 p.m.

Weight:

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

Course Summary:

Topics	Chapters in Dorato et al	Time table
Fundamental state-space Linear-Quadratic Regulator (LQR) problem	1,2	January 2012
Traditional feedback properties of LQR solution	3,4	February 2012
Review of stochastic processes, Kalman-Bucy filtering, and Linear Quadratic Gaussian (LQG) design	5,6	March 2012
Robustness aspects of LQG design: Loop Transfer Recovery (LTR) design	7	April 2012

Special topics: Students' choice between 1. *Digital LQ(G) control with applications to Active Queue Management or video streaming*	8	April-May 2012
2. *bounded real lemma introduction to H^{∞}design*	*	
3. *Quantum control: Kushner-Stratonovich integral or Continuous measurement equation* 4. *Financial engineering (Black-Schloes equation)*	**	

*I. R. Petersen, B. D.O. Anderson and E.A. Jonckheere, ``A first principles solution to the nonsingular H^{∞} control problem," *International Journal on Robust and Nonlinear Control*, vol. 1, pp. 171-185, 1991.
**Notes provided by Instructor.