ME 597B: OPTIMAL CONTROL OF ENERGY SYSTEMS

Course Syllabus, Section 001, Fall 2012

CLASS SCHEDULE

- Lectures:
  - On-campus: MWF 2.30pm-3.20pm, 327 Sackett Building
  - Online: available via Angel

- Office hours:
  - On-campus: MWF 3.30pm-5pm, 157D Hammond Building
  - Online (via Skype): By appointment; please email hkf2@psu.edu

REFERENCE MATERIALS

- Primary reference (required reading): Course notes, to be updated during the weekends on Angel. Students will be informed about the updates by email.

- Software: There is no required software for this course, but the instructor will use either Matlab® (available through student labs; there is also a ~$100 student license) or C/C++ (free for download), or OpenModelica (free for download) to illustrate class concepts. Students are welcome to use the same tools for their project work.

- Additional references (ordered by relevance, starting with most highly recommended):

PLAGIARISM

There is an inherent bond of trust and respect between faculty and students, and also among students. Plagiarism breaks this bond of trust and respect, and cannot be tolerated. Penn State University has formal policies and procedures regarding plagiarism. This course will strictly adhere to those policies and procedures.

To avoid suspicion of plagiarism, please make sure to adhere to at least the following five rules. First, never use the help of another individual on any piece of work unless this person is named explicitly as a contributor. Second, never use a reference without citing it carefully and fully. Third, remember that your colleagues and instructors trust and respect you, and think hard about the ethical standard you need to live up to in order to continue to earn this trust and respect. Fourth, remember that being fair is part of being honest, especially in the context of individual contributions to collaborative work. Fifth, whenever in doubt about whether an activity constitutes plagiarism, please ask before engaging in this activity.

1 Version 1, last edited 6/25/2012 by H. K. Fathy. Students will be informed promptly through Angel about further syllabus revisions (if any).
**COURSE SUMMARY**

This course examines the broad problem of controlling energy systems in a manner that optimizes their performance, efficiency, emissions, or long-term health.

**APPLICATIONS**

The course structure will be driven by applications such as maximizing the power output of photovoltaics and wind turbines, minimizing the fuel consumption and emissions of hybrid electric or hybrid hydraulic vehicles, maximizing the health of Lithium-ion batteries, or optimally dispatching grid energy storage to maximize renewable energy penetration.

**FOUNDATIONS**

Students will learn to tackle the above problems using the tools of optimal control, including extremum-seeking control, deterministic/stochastic dynamic programming, and linear quadratic regulation.

**OVERARCHING GOALS**

This course has five overarching goals:

1. To provide students with a panoramic introduction to the various tools and methods of optimal control and dynamic programming, with a strong emphasis on the assumptions, advantages/disadvantages, and numerical/fundamental strengths and weaknesses of each tool.
2. To explore at least six specific topics in optimal control theory in depth: optimality principles, extremum-seeking control, deterministic dynamic programming, stochastic dynamic programming, linear quadratic regulation, and model predictive control.
3. To illustrate the use of optimal control theory in the energy systems context, through examples pertaining to energy generation from both renewable and exhaustible resources, energy storage, and hybrid system power/energy management.
4. To give students some basic experience in writing and using optimal control software.
5. To engage students in high-quality research-flavored projects in the area of optimally controlling energy systems.

**BRIEF LIST OF MAIN TOPICS COVERED**

- **Fundamentals**
  - Optimality principles: Bellman’s principle of optimality, the Hamilton-Bellman-Jacobi equation, and the Pontryagin minimum principle
  - Extremum-seeking control
  - Shortest-path, finite-horizon deterministic dynamic programming
  - Infinite-horizon stochastic dynamic programming
  - Linear quadratic regulation
  - Model-predictive optimal control
  - Possible additional topics (most likely not covered) include: iterative optimal control; pseudo-spectral methods; combined plant/control optimization; optimal control for linear and convex systems; approximate dynamic programming; optimal control of singularly perturbed systems; optimal control of PDE systems; etc.
Applications
- Maximum power point tracking in photovoltaics
- IC engine brake specific fuel consumption (bsfc) minimization
- Energy-efficient airplane flight trajectory planning
- Optimal supervisory control in hybrid electric vehicles
- Optimal supervisory control in hybrid hydraulic powertrains
- Battery health-conscious optimal control
- Smart grid demand response to accommodate renewable (PV and wind) resource intermittencies
- Possible additional applications include: fuel cell control, combustion control, energy-efficient formation flight control, building energy management, data center energy management, smart grid generator dispatch, etc.

Grading

- Students will be scored out of 100 points.
- Cutoffs for various grades will be decided at the end of the term, possibly based on a curve. However, these cutoffs will not be higher than 95% for an A, 90% for an A-, 87% for a B+, 84% for a B, 80% for a B-, 75% for a C+, 70% for a C, and 60% for a D. This means that a student who scores 95%, for instance, is guaranteed to receive an “A”, while a student who scores 94.5% may or may not get an “A”, depending on the precise final grade cutoffs.
- Scores will be assigned based on:
  - Quick quizzes (15%):
    - Typically one quiz per week
    - Announced through Angel
    - To be solved by each student individually within an announced time frame
    - Students allowed to collaborate on quizzes, provided they report this collaboration as part of their quiz submission through Angel
    - Each quiz will typically cover material from preceding week, plus reading assignment for following week
    - Typically 3-10 multiple-choice or short-answer questions per quiz, solvable in 10-30 minutes
    - Best 90% of all quiz scores will count equally towards 20% of your grade
    - The goal is to incentivize students to attend class, read, and stay on top of the course material
  - Teaching experiences (15%)
    - Each student must individually:
      - Pick a fundamental topic of interest, relevant to the class
      - Get instructor approval for this topic
      - Find 3-5 excellent existing publications on the topic
      - Read these publications, and learn from them
      - Create a video-based mini-lecture/mini-tutorial (approx. 20-30 minutes) for classmates on this topic (note: these videos will be made available to the rest of the class)
      - The goal is twofold. First, to paraphrase Oppenheimer, the best way to learn a topic is to teach it. Second, graduate students interesting in becoming future faculty will benefit from having these “teaching experiences”.
  - Application case studies (30%)
    - We will cover 6-7 main optimal control tools in this course.
    - The instructor will make an announcement every time an optimal control tool has been covered fully.
Three weeks from the instructor’s announcements, students will have the option of individually submitting application case studies applying the presented optimal control tools to practical problems of interest to them.

Even though we will cover 6-7 optimal control tools, each student will only be required to complete three application studies.

For each application study, students should submit very brief reports (3-5 pages max., excluding source code) on these application studies. Each report should explain, very briefly:

- What problem it is trying to tackle (2-3 sentences max.)
- Why this problem is important (1 paragraph, max.)
- What references one can use to learn more about this problem (2-3 citations, max.)
- What the optimization problem is (written as a mathematical statement, 1-2 pages max.):
  - What is the optimization objective?
  - What are the optimization variables? Which of these optimization variables are static design variables, state variables, and/or input variables?
  - What are the optimization constraints?
  - What are the state-space equations governing the dynamics of the system?
  - What are the characteristics of the external disturbances – if any?
  - Note: please make sure to both present the optimization problem mathematically and explain the meanings of the different variables and equations and where you obtained them from.
- What method was used to solve this optimization problem, and what modifications – if any – had to be made to make the method suitable for the problem (1 paragraph, max.)
- What the optimal solution is, and whether it makes physical sense (1-2 pages, max.)
- Source code used to obtain the optimal solution (no page limit)

An ideal report should allow other students of comparable skill to understand the presented work fully after 20-30 minutes of reading, and replicate it in its entirety (by rewriting the optimization code from scratch) in no more than 3-5 hours of work. Note that these reports may be made available to the entire class, per the instructor’s discretion, solely for the benefit of the class.

The three application case studies will count for 30% of the overall grade.

The goal is to help students learn by using the tools presented in class to solve very simple application case studies of interest to them.

- Group R&D project (40%)
  - Students must work groups of 2-3
  - Each group must:
    - Pick one interesting energy system to control
    - Identify the objectives one should optimize in controlling this system (e.g., efficiency, emissions, long-term health, etc.)
    - Survey the literature on this system’s control
    - Identify the open research questions and gaps in this literature
    - Model this system from physics
    - Guesstimate the model’s parameters as accurately as possible
    - Formulate an optimal control problem for this system
    - Solve this problem using methods presented in class
• Analyze the solution, and evaluate its benefits and limitations
• Package the above work into a 6-8 page, double-column, 9-point “term paper”
• Also summarize the above work into a 20-minute video presentation
• Note that the above “term paper” and video presentation may be made available, per the instructor’s discretion, to the rest of the class for the benefit of the class.

- Each team’s project will be evaluated based on the above term paper and presentation
- All team members will receive the same project grade, unless there is irrefutable evidence of an egregious disparity in different members’ contributions
- Students are welcome to pick project topics grounded in their own graduate research. However, the work they do for the projects needs to be original.
- Based on previous experience, approximately 15-20% of all projects will be of at least solid conference publication quality\(^2\). Students are encouraged to try to publish their project work. Should this work be related to their own graduate research, they should include their advisors in authorship. For ethical reasons, the instructor for this class will not agree to be included in authorship on any publications resulting from the term projects.
- The goal is to engage students in mini-projects that have a genuine research flavor, thereby maximizing both their learning as students and productivity as researchers.

\(^2\) In fact, one paper produced by an ME 597B project team in the Fall semester of 2012 won the best paper award at the 2012 Penn State College of Engineering Research Symposium (PSU CERS 2012).