Master Course Syllabus for EE 448 (ABET sheet)

Title: Control Systems Laboratory

Credits: 4

UW Course Catalog Description

Application of control system analysis and synthesis techniques to electromechanical systems. Time and frequency domain methods. Analog and digital electronics, DC motors, and unstable mechanical systems. Prerequisite: EE 447. Offered: Winter

Coordinator: S. Burden, Associate Professor, Electrical and Computer Engineering

(Team) Faculty who are willing to teach this course:
Linda Bushnell, Blake Hannaford, Kim Ingraham, Sep Makhsous

Goals: To provide students with hands-on control engineering experiences that are relevant to design and operation of modern control systems. Applications include analog circuits, DC motors, inverted pendulum, and a balancing (segway-like) robot. Equal emphasis is placed on mathematical modeling, computational design, and experimental validation. Techniques include feedforward, feedback, PID, full-state, and observer-based control. This course prepares the student to solve real-world control system engineering design problems.

Learning Objectives: At the end of this course, students will be able to:

1. *Program* simulations of control systems and visualize the results using Python.
2. *Program* input and output from a microcontroller using CircuitPython, including serial communication and digital / analog IO pins.
3. *Measure* step and frequency response of an RC circuit using a microcontroller.
4. *Synthesize and test* feedforward and feedback (PI) control of an RC circuit voltage.
5. *Measure* aliasing in a digital control system.
6. *Synthesize and test* feedback control in an analog circuit using op amps.
7. *Measure* parameters of DC motor model.
8. *Synthesize and test* position control of DC motor using digital and analog controllers.
9. *Model* inverted pendulum.
10. *Synthesize and test* PID controller to stabilize inverted pendulum.
11. *Synthesize and test* state space controller to stabilize inverted pendulum.
12. *Synthesize and test* non-linear swing-up controller for inverted pendulum.
13. *Model and numerically simulate* balancing robot.
14. *Test* state space controller for balancing robot.

Textbook: None.

Prerequisite courses:
EE 447: Control Systems Analysis (4) -- Covers mathematical and computational techniques for analysis and synthesis of control systems.

Prerequisites by topic:

1. Can use Python to run simulations and analyze data.

2. Can mathematically and computationally model control systems in time and frequency domain.
3. Can synthesize stabilizing controllers that meet performance specifications.
4. Can apply PID and state space control techniques to stabilize a system.

Laboratory topics:

- *Lab 1 – Python (1 week)*: manage Python installation, run simulation of control system, save and load data from file, visualize simulation results.
- *Lab 2 – CircuitPython (1 week)*: program microcontroller using CircuitPython, read and write digital and analog pins, send and receive data over serial.
- *Lab 3 – RC Circuit (1 week)*: measure step and frequency response of RC circuit, compare with predictions from mathematical model. Implement feedforward and feedback (PI) control.
- *Lab 4 – DC motor (2 weeks)*: system identification of unknown parameters in DC motor model, control of velocity and angle using feedback control (PI and PD).
- *Lab 5 – inverted pendulum (2 weeks)*: modeling and system identification of unknown parameters in inverted pendulum, stabilization of unstable equilibrium using PID, state space, and non-linear swing-up controllers.
- *Lab 6 – balancing robot (1 week)*: mathematical modeling and simulations, controller design, optimal control methods, hardware testing.
- *Final project (2 weeks)*: open-ended control system project designed by students. Should incorporate a feedback loop in a fundamental way.

Final project topic examples:

- *Digital control*: measure frequency response of Sallen-Key circuit with varying sampling rates. Assess impact of sampling rate on feedforward and feedback (PID) control.
- *Analog control:* implement P, I, and D transformations using op amp circuits, use these electronics to control RC circuit, Sallen Key circuit, DC motor, and/or inverted pendulum.
- *Quadrotor*: implement detailed 3D simulation of quadrotor control system, stabilize the system through observer-based feedback, control the system to track a specified trajectory in state space.
- *Robot arm:* implement forward and inverse kinematics simulations, control trajectory of robot arm in configuration and task spaces, test on robot hardware.

Course structure: The laboratory meets for two 230-minute sessions per week overseen by the instructor and/or TAs, who start each session with an overview of the day's lab and any requisite background material (~30–60 minutes). For structured labs, students work individually at a lab bench using provided lab kits and lab assignments. Coursework for labs consists of reports submitted at the conclusion of each week. These reports contain responses to prompts interspersed throughout the lab assignment. For the final project, students propose a hardware or software project that demonstrates a feedback loop and considers real-world disturbances or unmodeled dynamics.

Computer resources: Completion of lab assignments requires knowledge of Python and word processing software, and basic breadboarding/circuit prototyping techniques.

Laboratory resources: Lab benches with power outlets, lockable cabinet for storing lab kits, and (optional) laptop or desktop computers. This course will require a technology fee to supply the lab kits.

Grading: Laboratory reports contain formative and summative assessments. The course syllabus and grading rubrics will clearly identify which components are summative and which are formative.

Laboratory Reports: 100%

- *Lab 1 – Python (1 week, 10%)*: visualization of simulation results.
- *Lab 2 – CircuitPython (1 week, 10%)*: communication with microcontroller, simulation results.

- *Lab 3 – RC Circuit (1 week, 10%)*: frequency response, feedforward and feedback control.
- *Lab 4 – DC motor (2 weeks, 20%)*: system identification, control of velocity and position.
- *Lab 5 – inverted pendulum (2 weeks, 20%)*: system identification, stabilization, swing-up control.
- *Lab 6 – balancing robot (1 week, 10%)*: simulation results, optimal controller, stabilization.
- *Final project (2 weeks, 20%)*: demonstration of feedback loop in novel control system.

It is highly recommended that part of the lab assignment grading include a direct, face-to-face laboratory demonstration that verifies that each student is learning the hands-on laboratory skills for which the course is designed and also minimize academic dishonesty. If students work in teams to complete the laboratories, a means for ensuring that each student contributes something meaningful to each laboratory report is strongly recommended.

ABET student outcome coverage: This course addresses the following outcomes:
H = high relevance, M = medium relevance, L = low relevance to course.

(1) *An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.* **(H)**

Each of the lab assignments deals with quantitatively applying fundamental principles of control system engineering using mathematical and computational expertise acquired from previous courses.

(6) *An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions* (H)

In most labs, students will build and/or collect data from electromechanical systems. Students will be required to compare experimental data to simulated or theoretical data to understand the impact of real-world operation and device variation on performance.

Prepared By: Sam Burden
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Additional information and resources regarding teaching ECE courses (e.g., links to course repositories for materials from previous course offerings; guidelines for using AI tools in courses; syllabus language for course accommodations, etc.) can be found on the UW ECE Intranet:
https://peden.ece.uw.edu/academic-ops/