Sampled-Data and Digital Control Systems
Simulation Laboratories and Projects

The simulation laboratories or projects you will do in this course are meant to provide a more hands-on and personal view of the control techniques we discuss in class (and their limitations). You will have the choice of doing *either* the two simulation laboratories *or* designing a project that is more tailored to your interests, based upon your background and other experiences. In the simulation labs, you will implement digital controllers using the Matlab and Simulink software packages. By experimenting with the simulations, you will demonstrate for yourself the limitations of designing digital controllers by approximating continuous ones and the value of directly designing compensators in the discrete domain. In the projects, you may choose to design a project that is inspired by the simulation laboratory handouts, or design a completely separate project that explores some aspect of sampled-data and digital control systems in more detail.

Lab or Project Report Format

Below are some suggestions for your lab or project reports. Lab reports are expected to follow this format as closely as possible – as this guideline closely resembles the lab report grading criteria. Project reports may deviate from this exact format depending on the nature of the project. Be sure to discuss novel or radical departures from these guidelines with me.

Please turn in one report per person for each lab or project. Reports should be turned in electronically via Canvas, as they will most likely be prepared electronically. Each report should consist of a cover page and supporting analysis, results, discussion, and conclusion sections.

Cover Page and general format: (approximately 5 points) The cover page should indicate your name, the course, the lab number/title or project title, the professor's name, name of lab/project partner, and the date submitted. A brief table of contents should be provided indicating the major sections in the report and their page numbers. Page numbering in the report is required.

Supporting Analysis: (approximately 20 points) This section can be identical to your partner's. The Supporting Analysis section should include important steps in the calculations used to derive controllers and those used to predict the performance of the controllers. If appropriate, results of several different cases can be tabulated. For example, when describing a set of compensators, pole and zero locations should be listed.

Results: (approximately 35 points) This section can also be identical to your partner's. A summary of results should be included at the beginning of the Results section, indicating briefly what simulations were run and the order in which data will be presented. Be sure to label all curves and have a *self-explanatory and descriptive* title for every graph. Tabulate the important observations from the data if appropriate. For example, for a step response experiment, the overshoot, rise time, and perhaps settling time and damping ratio should be determined from the data.

Discussion: (approximately 25 points) Each student must write this section individually, but you may discuss the content with your partner or others. This section should include important observations made by comparing the theory and simulations, referencing plots where necessary. Comment on differences between results and predictions made in the supporting analysis. Also comment on the design methods, such as their ease of use and performance. Discuss any sources of error in the simulation experiments.

Conclusions: (approximately 15 points) Each student must write this section individually, but you may discuss the content with your partner or others. Describe concisely what was learned from the lab or project and how these lessons may be applied.

Note: The report should be of a reasonable length. Conciseness is encouraged.

Simulation Labs

If you choose to do the simulation labs, you will complete two labs during this course:

Lab 1:	Discrete Equivalent Designs versus Direct Discrete Designs: In this lab, you will first design discrete controllers by converting classically designed continuous compensators into "equivalent" digital compensators. The performance of these will then be compared with digital compensators directly designed in the discrete domain using the root locus technique.
Lab 2:	Digital Control using State Variables: The design of digital compensators in the z-plane using the state variable approach will be used for this lab.

Projects

If you choose to design a project that is more tailored to your interests and other experience, you will be asked to turn in a project summary and short project progress reports periodically and meet with me to discuss your project:

Project Summary. Turn in a summary (one to three pages) of your proposed project by 6pm on February 12.

Project Progress Report 1: Turn in, by 6pm on February 26, a short progress report (one to three pages) providing an update on your project and outline any changes to your original proposed project.

Project Progress Check Meeting: During March 17-21, along with your project partner, meet with me to discuss your project. Hopefully by this point, the project is quite well-defined, and you and your partner are clear on your roles and tasks in the project.

Project Progress Report 2: A second "progress report" (one to three pages) will be due by 6pm on April 9.

These "progress reports" are mostly to make sure that you stay on track with making progress on your project, and I will do my best to provide constructive feedback on these. Some more details regarding these progress reports may be provided with the homework handouts throughout the semester. Final complete project reports are due by 6pm on April 28, which is the same due date as for Simulation Lab 2 reports.

Sample Project Ideas

Below are some project ideas. You may choose to design a project based on one of these ideas, or design another project of your choosing. The only requirement is that the project topic should be related to sampled-data and digital control.

1. Choose one particular plant $G(s)$ of interest, and work through the tasks of the two Simulation Labs. Explain why $G(s)$ is of interest to you, and why it might be of general interest to others. Your $G(s)$ should be at least 2nd-order, and no higher than 4th-order. If you really want to choose a higher-order $G(s)$, be sure to discuss things with me. Your progress reports should outline how any of the tasks may need to be changed in light of the particular $G(s)$ you have chosen.

2. Choose one particular plant $G(s)$ of interest, design a continuous-time controller in order to meet some performance specifications, and then design discrete equivalent digital controllers with all of the numerical integration techniques we discuss or touch upon in class: forward rectangular rule, backward rectangular rule, bilinear rule, bilinear with prewarping, zero-pole mapping, zero-order-hold equivalent, triangular-hold equivalent. Design a direct z-plane compensator and compare performance results. Design a state-space based controller and compare results.

3. Choose one particular plant $G(s)$ of interest. Augment this plant with a Padé approximation of a delay of $T/2$. That is, multiply the plant transfer function with the Padé approximation, and call the result the augmented plant. Design a compensator $D(s)$ for the augmented plant for a range of sample periods T. Choose a particular sample period T and design several discrete equivalent compensator designs with this sample period. Implement the resulting discrete compensators $D(z)$ to control your original (non-augmented) plant $G(s)$, and simulate the performance. Does the performance match well with what is predicted by the corresponding continuous-time control loop with the Padé approximation? Explore how the results change when using different Padé approximations (e.g., first-order, 2nd-order, or higher-order approximations). Investigate state-space compensator designs, and how the delay of $T/2$ can be represented in an augmented state-space representation of the plant. Compare the performance of the state-space designs with the transfer function designs.

4. Explore how sampling gives rise to discrete equivalents that have unstable zeros. In particular read the following classic paper (posted on course website):

   K. J. Astrom, P. Hagander, and J. Sternby, "Zeros of Sampled Systems," *Automatica*, Vol. 20, No. 1, pp. 31–38, 1984.

   Choose a couple plants $G(s)$ and analyze how, and under what circumstances, the discretized sampled plants $G(z)$ may have unstable zeros. What are the ramifications of unstable plant zeros? Design and compare a few digital controllers for the various $G(z)$ you have.

Selected actual projects that have been carried out in past years include:

- Digital control of a pressure algometer to study human pain thresholds
- Plant and controller development for a soft robot
- Electromagnetic position control for a magnetic levitation system
- Digital feedback control for an RF power amplifier
- Discrete analysis and implementation of a magnetically actuated controller for a cube satellite
- Satellite pitch control of simplified (4th-order) model of the Hubble Space Telescope
- Power reference tracking control for a wind turbine
- Voltage regulation in a 100 MHz CLL resonant DC-DC converter

- Control of a bi-directional flyback converter for solar panel power transfer, with hardware verification on research lab setup
- Exploration of non-minimum phase zeros and intersample ripple in sampled-data control systems (with 3rd and 4th-order continuous-time plants), which led to the publication of a conference paper[1] (posted on course website)
- Modeling and digital control of a quadcopter
- Control of an autonomous underwater vehicle
- Digital control of an inverted pendulum, including hardware demonstration using a setup available through ITLL
- Trajectory tracking with vibration suppression of a model robot manipulator with single flexible link

Incentives for Doing Projects

Since it may be easier for most students just to do the relatively well-outlined simulation labs rather than design their own projects, here are some incentives for choosing to do a project:

a. Each "progress report" required of those who do projects will be graded on a scale from 0 to 10, and these (up to 10) points will be counted as extra credit on the corresponding homeworks around when the progress reports are due. That is, your Project Summary score will be added to your Homework 3 score; your Project Progress Report 1 score will be added to your Homework 4 score; your Project Progress Check Meeting score will be added to your Homework 5 score; and your Project Progress Report 2 score will be added to your Homework 6 score.

b. The simulation labs have extra credit portions, where students can earn up to 10 additional points per lab, for a total of up to 110 points per lab report. Depending upon the design of your project, your project will be given up to 10 extra points (on your final project report score) for creativity and comprehensiveness, since there is extra effort that must go into designing a project well. Additional extra credit points (likely up to 5 points) may be earned on projects depending upon their complexity. These should be discussed with me ahead of time, or I may give these at my discretion when grading the project reports.

Final Notes on Project/Lab Grading

As mentioned in the Syllabus, Projects / Simulation Labs will count for 20% of your course grade. I will compute your overall Project / Simulation Labs score as follows.

If you are doing the labs, your overall Simulation Lab score will be:

$$\begin{aligned}\text{Simulation Lab score} \;&=\; (\text{Simulation Lab Report 1 score} + \text{Simulation Lab Report 2 score} \\ &\quad + \text{Lab Presentation score})/3\end{aligned}$$

If you are doing a project, your overall Project score will be:

$$\text{Project score} = [2 \times (\text{Final Project Report score}) + \text{Project Presentation score}]/3$$

[1] H. Chen, Y. Li, and L. Y. Pao, "Intersample Ripple Resulting from Discrete-Time Feedforward Control," *Proc. American Control Conf.*, Washington, D.C., pp. 4122-4127, June 2013.

Presentation scores will be determined based on the organization and clarity of your slides and your explanations, ability to answer relevant questions that are posed in the follow-on question and discussion period, and appropriate length of presentation given the guidelines.

All students are encouraged to attend all presentations. There may be a few short-answer questions (worth a couple points each) on the Midterm and/or Final Exams related to key points made in the Simulation Lab and Project presentations.

Addendum (February 3, 2025):
Since our class is very small, I am offering extra credit if you make 2 presentations (Simulation Lab 1 and Simulation Lab 2 presentations; or Intermediate and Final Project presentations), then the overall Simulation Lab and Project Scores will be computed as follows:

$$\begin{aligned}\text{Simulation Lab score} &= (\text{Simulation Lab Report 1 score} + \text{Simulation Lab Report 2 score} \\ &\quad + (\text{Average of both Lab Presentation scores}) \times 1.5)/3\end{aligned}$$

$$\begin{aligned}\text{Project score} &= [2 \times (\text{Final Project Report score}) \\ &\quad + (\text{Average of Intermediate and Final Project Presentation scores}) \times 1.5]/3\end{aligned}$$