

# EENG307: Introduction to Feedback Control Systems

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Semester/Year: Spring 2017

## 1 Syllabus

### Course Info

- Class meeting schedule: Section A: MWF 11:00-11:50am, Section B: MWF 10:00-10:50am Section C: TR 9:30-10:45am, Section D: MWF 2:00-2:50pm, Section E: MWF 4:00-4:50pm.
- Class location: Section A: Green Center 215, Section B: Brown Building W250, Section C: Brown Building W210, Section D: Berthoud Hall 241, Section E: Brown Building W210.
- Course Webpages:
  - Canvas (<http://elearning.mines.edu/>). All current CSM students should have a Canvas account, and students registered for this course will be automatically enrolled. Check with CCIT if you do not have an account. Canvas will be used to post homework assignments, submit homework assignments, view grades, and other section-specific material.
  - Piazza (<http://piazza.com/mines/Spring2017/eeng307>). Piazza will be used as a QA forum for content and general questions. (Preferred to email.) Piazza will also be used to post lecture notes and other material for all sections.

### Instructors

- Section A and B - Christopher Coulston
  - Office: BB310F
  - Office hours: MWF 12:00 - 1:30 pm
  - Email: coulston@mines.edu
- Section C - Adewole Ayoade
  - Office hours location: W478
  - Office hours: TWR 11:00am - 12:00 noon
  - Email: aayoade@mymail.mines.edu
- Section D - Tyrone Vincent
  - Office: BB327D
  - Office hours: M 3-4:30pm, Tu 1:00-2:30 pm
  - Email: tvincent@mines.edu
- Section E - Hisham Sager

- Office hours location: BB329
- Office hours: M 10:00-11:00 AM, W 10:00-11:00 AM
- Email: hsager@mines.edu

Note: Offices and office hours may change, please check Canvas or Piazza for the latest information.

**Instructional Activity:** 3 hours lecture, 0 hours lab, 3 semester hours.

**Course designation:** Major Requirement (EE and ME)

**Course description from the Bulletin:**

System modeling through an energy flow approach is presented, with examples from linear electrical, mechanical, fluid and/or thermal systems. Analysis of system response in both the time domain and frequency domain is discussed in detail. Feedback control design techniques, including PID, are analyzed using both analytical and computational methods.

**The Textbook (Optional)**

Gene F. Franklin, J. David Powell, Abbas Emami-Naeini, *Feedback Control of Dynamic Systems*, 7th Edition. ISBN 013601969-2.

**Objectives**

**Students will be able to:**

- Develop mathematical models for linear dynamic systems (mechanical, electrical, fluid and thermal).
- Use time domain and frequency domain tools to analyze and predict the behavior of linear systems.
- Use time domain and frequency domain techniques to design feedback compensators to achieve a specified performance criterion.
- Use MATLAB for system analysis and design.

**Topics Covered**

See Schedule at end of this document.

**Letter Grades**

Letter grades will be assigned as stipulated in the undergraduate bulletin <http://bulletin.mines.edu/undergraduate/undergraduateinformation/undergraduategradingsystem/>

- A  $\geq$  90
- B+  $\geq$  87
- B  $\geq$  83
- B-  $\geq$  80
- C+  $\geq$  77
- C  $\geq$  73
- C-  $\geq$  70
- D+  $\geq$  67
- D  $\geq$  63
- D-  $\geq$  60
- F Failed

## Grading Scale

### Available Points

Exam 1	Prep Score	7%
	Exam Score	18%
Exam 2	Prep Score	7%
	Exam Score	18%
Exam 3	Prep Score	7%
	Exam Score	18%
Final Project		25%
Total		100 %

### Prep Score

The course is split into three intervals, each one associated with an exam. During each interval there will be

- 1 In-Class Quiz score - 10 points total
- 4 Homework Assignments - 10 points each
- 2 Canvas Quizzes - 10 points each

Each prep score is out of 50 points, which includes the best 5 of the 7 scores from the group of in-class quizzes, homework and Canvas quizzes. In addition, there are bonus **prep** points:

- Typo Bonus Points - If you find a typo in the notes, the first to report it on Piazza gets 1 bonus point
- Endorsed Answer Bonus Point - If you post an answer on Piazza that is endorsed, you get 1 bonus point

You can earn up to 12 bonus points. For simplicity, on Canvas, all bonus prep points are added to the first prep score, no matter when they are earned.

### Prep 2 Qualification Quiz

Starting in interval 2, familiarity with complex numbers becomes very important. Thus, for interval 2, there is an additional quiz verifying your knowledge of complex numbers. Your final Prep 2 score will be adjusted by a multiplier that depends on the Complex Number Qualification Quiz:

Points on the Quiz	Prep 2 multiplier
7.5-10	100%
5	75%
2.5	50 %
0	0 %

You will have three chances to take the Complex Number quiz and your highest score will count.

### In-Class Quizzes

- You will be working in groups of 3-4 people. You will self select your group in Canvas. This also your project group.
- Marked quiz problems
  - Some homework problems will be marked as "Quiz Problems" for a particular day. You would work these problems before coming to the lecture that day.
  - Before the quiz, you will have several minutes to discuss the quiz problems with your group.

- Unmarked quiz problems
  - Occasionally, other homework problems may also be worked as examples during class time.
- In-class quizzes will be scored using i-clickers, which can be purchased in the bookstore. **Register your clicker on <http://iclicker.com>.** Use your Canvas login id in the student ID field. If you make a mistake registering, just register again.
- There will be at least 6 quizzes during each of the three course intervals. You will get 1 point per answer, plus 1 point per correct answer, up to a max of 10 points.

### Homework

- Homework is assigned weekly.
- At least partial credit is given for each problem with a legitimate attempt. Problems may be graded unequally.
- *All* homework problems should be submitted, even ones that have been quizzed on in class.
- Homework is due at 5:00pm on the due date.
- Homework can be turned in (early) in class. Otherwise homework must be turned in on Canvas. It must be submitted as a .pdf file, and it is your responsibility to ensure that it has been uploaded correctly.
- *Do not* turn in homework to my mailbox or slip under my door.
- **No late homework is accepted for any reason.**

### Exams

- Mid-term exams:
  - There will be three in class exams during the semester, with dates given in the schedule below. Note these dates and plan accordingly!
- No calculators are allowed in the exams. Graphs of important functions will be provided, but you will need to be able to do simple arithmetic by hand. You may not use your phone during exams. However, slide rules are allowed!

### Coursework Return Policy

All homework assignments will be returned the week after they are due. Exams will be graded and returned as quickly as possible, no later than 2 weeks after the exam.

### On-line lectures

- Several times during the semester, video lectures will be made available.
- All students are expected to watch the video before the corresponding lecture date.
- The extra class time will be used to work problems and answer questions.

## **Absenteeism**

- Sports/Activities Policy
  - Alternate scheduling will be made available for exams, but no other assignment.
  - Schedule alternate exam times two week prior.
- Flu
  - If a student is ill and exhibits flu-like symptoms, they should not attend class, labs, or exams.
  - Notify your instructor via e-mail.

From the bulletin:

### **Absenteeism**

Class attendance is required of all undergraduates unless the student is representing the School in an authorized activity, in which case the student will be allowed to make up any work missed. Students who miss academic work (including but not limited to exams, homework, labs) while participating in school sponsored activities must either be given the opportunity to make up this work in a reasonable period of time or be excused from such work. It is the responsibility of the student to initiate arrangements for such work. Proof of illness may be required before makeup of missed work is permitted. Excessive absence may result in a failing grade in the course. Determination of excessive absence is a departmental prerogative.

The Office of the Dean of Students, if properly informed, will send a notice of excused absence *of three days or more* to faculty members for (1) an absence because of illness or injury for which documentation will be required; (2) an absence because of a death in the immediate family, i.e., a spouse, child, parent, grandparent, or sibling. For excused absences the student must be provided the opportunity to make up all missed work.

## **Classroom Rules**

- Please help your classmates focus!
- Keep unrelated discussions to a minimum.
- Quiet food and drink only - no potato chips, do not open sodas during class.
- Participate in class-room exercises.
- Laptops in last row only. (Tablets used for active note-taking excepted.)
- No cell phone use, including texting. Using cell phones distracts your professors and therefore makes it harder for your classmates to learn. If you have an important call, please take it outside the classroom.

## **Academic Honesty**

The Colorado School of Mines affirms the principle that all individuals associated with the Mines academic community have a responsibility for establishing, maintaining and fostering an understanding and appreciation for academic integrity. In broad terms, this implies protecting the environment of mutual trust within which scholarly exchange occurs, supporting the ability of the faculty to fairly and effectively evaluate every student's academic achievements, and giving credence to the university's educational mission, its scholarly objectives and the substance of the degrees it awards. The protection of academic integrity requires there to be clear and consistent standards, as well as confrontation and sanctions when individuals violate those standards. The Colorado School of Mines desires an environment free of any and all forms of academic misconduct and expects students to act with integrity at all times.

Academic misconduct is the intentional act of fraud, in which an individual seeks to claim credit for the work and efforts of another without authorization, or uses unauthorized materials or fabricated information in any academic

exercise. Student Academic Misconduct arises when a student violates the principle of academic integrity. Such behavior erodes mutual trust, distorts the fair evaluation of academic achievements, violates the ethical code of behavior upon which education and scholarship rest, and undermines the credibility of the university. Because of the serious institutional and individual ramifications, student misconduct arising from violations of academic integrity is not tolerated at Mines. If a student is found to have engaged in such misconduct sanctions such as change of a grade, loss of institutional privileges, or academic suspension or dismissal may be imposed.

The complete policy is online.

For this course, the following rules should be followed:

- All students must turn in individual homework (unless otherwise stated) and they must understand what they turn in.
- Copying of solutions without understanding them is not allowed; if a student copies a solution and cannot explain it adequately this is considered academic dishonesty.
- For computer exercises, each student is expected to generate his/her own solution (i.e. one cannot simply copy another person's computer solution and modify it slightly to make it look like it is your own work).
- During quizzes and exams (both in-class and take-home), students must do 100 percent of the work on their own.
- The nominal penalty for academic dishonesty is an 'F' in the course.

## **MATLAB**

- A tool for technical computing with a programming like interface. (You should have already taken Fortran, C, or Java.)
- Easy access to highly optimized numerical methods.
- You are responsible for becoming familiar with the MATLAB interface. If you are unfamiliar with MATLAB, we would recommend purchasing an introductory text, or make use of the myriad tutorials on the internet.
- You will also find some introductory information about MATLAB in your textbook at the end of most chapters and in the appendix.
- Instructions for accessing MATLAB from your laptop (called remote access) can be found here: <http://inside.mines.edu/Matlab>.

## **2 Resources**

### **Resources**

There are numerous resources available to help you learn the course material. They include:

- Lectures (in class)
- Electronic lecture files (available on Canvas), with self quizzes at the end of each lecture
- Homework problems and solutions (posted on Canvas)
- Quizzes (posted on Canvas)
- Exam solutions (posted on Canvas)

**More Resources!**

- Your professors (office hours, email)
- Piazza - post a question or answer a question, we will be moderating this frequently.
- Students are encouraged to seek academic support if struggling with course material. Information on Tutoring, Academic Excellence Workshops, and Academic Coaching can be found at <http://academicservices.mines.edu>.

**Disability Support Statement:**

The Colorado School of Mines is committed to ensuring the full participation of all students in its programs, including students with disabilities. If you are registered with Disability Support Services (DSS) and I have received your letter of accommodations, please contact me at your earliest convenience so we can discuss your needs in this course. For questions or other inquiries regarding disabilities, I encourage you to visit <http://disabilities.mines.edu> for more information.

### 3 Schedule

(Note: this schedule is subject to change)

Date	Topic	Lec.	Assignments
Tue, January 10	<b>Introduction to Control Theory:</b> Examples, motivation, roadmap of the course		
Wed, January 11	Modeling Mechanical Systems	1	
Fri, January 13	Modeling Electrical Systems	2	
Mon, January 16	<b>Martin Luther King Day - No Class</b>		
Wed, January 18	Laplace Transform Review	3	Homework #1 Due
Fri, January 20	Solving Differential Equations using Laplace Transforms, Part I	4	
Mon, January 23	Solving Differential Equations using Laplace Transforms, Part II	5	
Wed, January 25	Impedance and Transfer Functions	6	Homework #2 Due
Fri, January 27	Fluid Systems and System Analogies	7	
Mon, January 30	Mechanical Impedance	8	
Wed, February 1	Thermal Systems	9	Homework #3 Due
Fri, February 3	Block Diagrams	10	
Mon, February 6	Motors and Hydraulic Actuators	11	
Wed, February 8	Time Response of First Order Systems	12	
Fri, February 10	Time Response of Second Order Systems	13	Homework #4 Due
Mon, February 13	Review for Exam		
Wed, February 15	<b>Exam # 1</b>		
Fri, February 17	Time Response of Higher Order Systems	14	
Mon, February 20	<b>President's Day - No Class</b>		
Wed, February 22	System Identification	15	Homework #5 Due
Fri, February 24	Stability and Routh Hurwitz Criterion	16	
Mon, February 27	Disturbances and Steady State Error	17	
Wed, March 1	Reference Steady State Error and System Type	18	Homework #6 Due
Fri, March 3	Proportional, Integral, and Derivative (PID) Control	19	
Mon, March 6	Introduction to Root Locus	20	Complex Number Qualification Quiz Due
Wed, March 8	Root Locus Examples	21	Homework # 7 Due
Fri, March 10	PD Design Using Root Locus	22	

Date	Topic	Lec.	Assignments
Mon, March 13	Sinusoidal Steady State	23	
Wed, March 15	Bode Plots for First Order Systems	24	Homework #8 Due
Fri, March 17	Make Up Day		
Mon, March 20	Review for Exam		
Wed, March 22	<b>Exam #2</b>		
Fri, March 24	Bode Plots for Second Order Systems	25	
Mon, March 27	<b>Spring Break through March 31 - No Class</b>		
Mon, April 3	Bode Plots for Higher Order Systems	26	
Wed, April 5	Bode Plot Examples	27	Homework #9 Due
Fri, April 7	Nyquist Stability Theorem	28	
Mon, April 10	Nyquist Stability Analysis	29	
Wed, April 12	Gain and Phase Margin	30	Homework #10 Due
Fri, April 14	Systems with Time Delay	31	
Mon, April 17	Time/Frequency Relationships	32	
Wed, April 19	Frequency Domain Analysis of Proportional Control	33	Homework #11 Due
Fri, April 21	<b>E-Days, No Class</b>		
Mon, April 24	Review for exam		
Wed, April 26	<b>Exam #3</b>		
Fri, April 28	Frequency Domain Analysis of PD Control	34	
Mon, May 1	Frequency Domain Analysis of PI Control	35	
Wed, May 3	Project Day		Homework #12 Due

## 4 Pre-Req Review

This class will make extensive use of complex numbers, so it is important that you are comfortable with their use. The following problems are for you to test your knowledge. If these seem difficult, please see the complex-number review available on Canvas.

1. Convert the following to rectangular form:

(a)  $z = \sqrt{2}\angle -\frac{\pi}{4}$

(b)  $z = 1\angle\frac{\pi}{2}$

(c)  $z = 1\angle\pi$

(d)  $z = 1\angle\frac{7}{4}\pi$

2. Plot the following complex numbers in the complex plane, and convert to polar form:

(a)  $z = 1 + \sqrt{3}j$

(b)  $z = -2$

(c)  $z = -\sqrt{2} + \sqrt{2}j$

(d)  $z = -\sqrt{2} - \sqrt{2}j$

3. Simplify the following to a complex number in rectangular form:

(a)  $1\angle -\pi + 2\angle\pi/2$

(b)  $j(1\angle\pi/4)$

(c)  $1 + 1\angle\pi/4$

(d)  $(1 + j)^*$

4. Simplify the following to a complex number in polar form:

(a)  $(1 + j)^2$

(b)  $\frac{2j}{1+j}$

(c)  $(2\angle -\pi/4)^*$

### 4.1 Solutions

1. Convert to rectangular form

(a)  $\sqrt{2}\angle -\frac{\pi}{4} = \sqrt{2}\cos(-\pi/4) + j\sqrt{2}\sin(-\pi/4) = 1 - j$

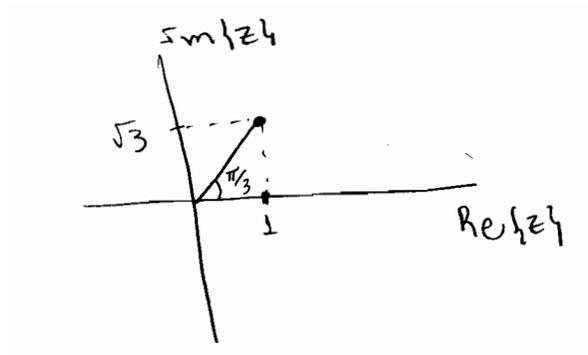
(b)  $1\angle\frac{\pi}{2} = \cos(\pi/2) + j\sin(\pi/2) = j$

(c)  $1\angle\pi = \cos(\pi) + j\sin(\pi) = -1$

(d)  $1\angle\frac{7}{4}\pi = \cos(7\pi/4) + j\sin(7\pi/4) = \frac{\sqrt{2}}{2} - \frac{\sqrt{2}}{2}j$

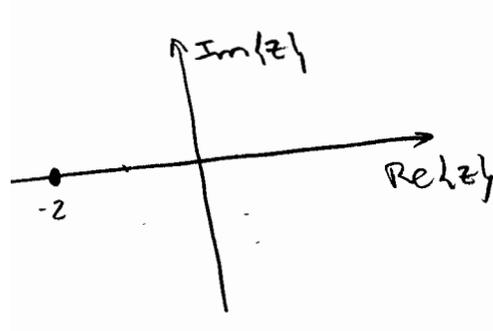
2. Graph and convert to polar form

(a)  $z = 1 + \sqrt{3}j$



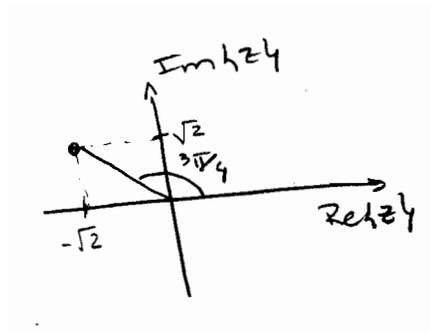
$$z = \sqrt{1+3} \angle \tan^{-1}(\sqrt{3}) = 2 \angle \pi/3$$

(b)  $z = -2$



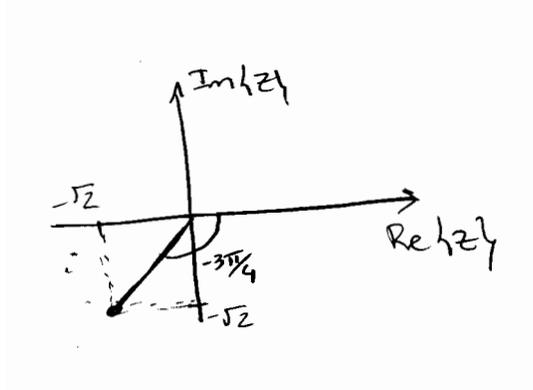
$$z = 2 \angle -\pi$$

(c)  $z = -\sqrt{2} + \sqrt{2}j$



$$z = \sqrt{2+2} \angle (\pi - \tan^{-1}(1)) = 2 \angle 3\pi/4$$

(d)  $z = -\sqrt{2} - \sqrt{2}j$



$$z = \sqrt{2+2} \angle (-\pi + \tan^{-1}(1)) = 2 \angle -3\pi/4$$

3. Simplify to a complex number in rectangular form

(a)

$$1 \angle -\pi + 2 \angle \pi/2 = -1 + 2j$$

(b)

$$\begin{aligned} j(1 \angle \pi/4) &= j \left( \frac{1}{\sqrt{2}} + j \frac{1}{\sqrt{2}} \right) \\ &= -\frac{1}{\sqrt{2}} + j \frac{1}{\sqrt{2}} \end{aligned}$$

(c)

$$\begin{aligned} 1 + 1 \angle \pi/4 &= 1 + \frac{1}{\sqrt{2}} + j \frac{1}{\sqrt{2}} \\ &= \frac{1 + \sqrt{2}}{\sqrt{2}} + j \frac{1}{\sqrt{2}} \end{aligned}$$

(d)

$$(1 + j)^* = 1 - j$$

4. Simplify the following to a complex number in polar form:

(a)

$$\begin{aligned} (1 + j)^2 &= (1 + j)(1 + j) \\ &= 1 + 2j - 1 \\ &= 2j \\ &= 2e^{j\pi/2} \end{aligned}$$

(b)

$$\begin{aligned} \frac{2j}{1 + j} &= \frac{2j(1 - j)}{(1 + j)(1 - j)} \\ &= \frac{2 + 2j}{2} \\ &= 1 + j \\ &= \sqrt{2}e^{j\pi/4} \end{aligned}$$

(c)

$$(2\angle - \pi/4)^* = 2\angle \pi/4$$