2.70 2017 FUNdaMENTALS of Precision Product Design
3-3-6

Examines design, selection, and combination of machine elements to produce a robust precision machine or system. Introduces process, philosophy and physics-based principles of design to improve and enable renewable power generation, energy efficiency, and manufacturing productivity. Topics include linkages, power transmission, screws and gears, actuators, structures, selection of materials, joints, bearings, error apportionment, and error budgeting. Considers each topic with respect to its physics of operation, mechanics (strength, deformation, thermal effects) and accuracy, repeatability, and resolution. Includes guest lectures from practicing industry and academic leaders. Students design, build, and test a small benchtop precision machine; this year’s default project is a computer-controlled desk that can raise/lower to be used when standing or sitting. Prior to each lecture, students review the pre-recorded detailed topic materials and then converge on what parts of the topic they want covered in extra depth in lecture. Students are assessed on their preparation for and participation in class sessions. Students taking graduate version are expected to complete additional assignments.

Pre-requisites:
1. Course 2.008 or 2.75 AND/OR ALL students in this class MUST be competent in a machine shop, and have SECURED ON THEIR OWN access to a machine shop to complete the hardware assignments. Students must also be skilled using 3D CAD software (e.g., SolidWorks):
   a. In SW know how to create dimensioned drawings and a Bill of materials, as well as use part configurations...
   b. Students need to be good at finding stuff (building materials) as very little will be supplied. All the assignments can be completed using scrounged materials, but this also allows students who really want to make a nifty machine for themselves to do so.
2. There is no textbook purchase required, Prof. Slocum wrote the book and it is freely downloaded. However, before class starts, each student is responsible for acquiring a microcontroller board (e.g., Arduino or Raspberry Pi) and interfacing it with their computer (desktop or laptop is preferred), and controlling the motion of a simple servo or stepper motor.
   a. Prof. Slocum’s assistant will provide a stepper motor to students who see her with a microcontroller operated from their laptop (e.g., turn on an LED).
   b. NOTE this may seem open ended, but there is so much info on the web, and from friends... Consider this the entrance ticket to the class that shows you are resourceful 😊.
   c. This should be familiar to students (from 2.007 and 2.670)
3. All lectures and “in class exams to help better comprehend lecture material” will be done by students using the 2.75x platform. Thus in class students can ask the teacher to expand on particular items from the lecture materials!
   a. FUNdaMENTALS text can be downloaded from the 2.75 or 2.75x sites.
4. It is strongly suggested that students complete the 2.75x course and on-line exams in IAP before the class begins!
   a. Total 100% focus can then be on the term project machine design.

Learning Objectives
1. Develop and demonstrate a deep understanding of deterministic design: everything happens for a reason:
   a. Prayer may be good in one’s personal life, but not for machine design.
2. Understand the functional operation and governing physical laws of machine elements:
   a. Continually read trade magazines (e.g., Design News) to learn what exists, how it works, why it works, how to properly use it, to enable a designer to select/buy if possible so you do not reinvent the wheel
   b. Be able to examine everyday machines and understand why certain machine elements are used and be able to approximate their capabilities
3. Conceive an overall machine system, and an analytical model to deterministically guide the design (e.g., error apportionment and error budget) to meet functional requirements:
   a. Complete a detailed design of a machine with predicted accuracy, stiffness, and life; and then build and test. Design is consequent to the last detail - machines will match their models and their performance characterized before any building and testing.
   b. Hone your skills at machining parts and assembling them into machines – overly complex and intricate parts mean more time spent by you in a machine shop!
   c. Basic interface to computer control system to move a machine
4. Be good, honest, constructive peer reviewers; be open to constructive criticism, and know how to graciously handle flames from aft ejection orifices.
5. Create/maintain personal website. All assignments from 2.70 must be posted to your personal website. Since assignments will be done professionally and peer reviewed they can be a very positive addition to your portfolio!
6. Documentation:
   a. Integral to maintaining website – pictures needed for assignments etc., Lab notebooks or journals are required for sketching and peer review
      i. Part of the satisfaction of design is seeing how far you have come since your started. This should be a fun and rewarding experience!
7. No whining!
   a. Think! Anticipate!
      i. Ask yourself “what would I want to see as the customer (professor, manager ..)?
   b. This is to be a fun course for students and staff to learn together to become even better machine designers!
c. If you want something, find it (get it) yourself! 😊

**Grading**

1. This is not a course for people who want handholding and who try and count points each week to ensure they have a grade they need for their GPA...
2. Students who carefully listen and focus and want to learn will do great!
   a. Your most excellent reflection on abilities learned will be your website you can show to potential employers/grad schools. A letter grade means nothing compared to what you show you can do!
3. Qualitatively grades in this class mean:
   a. *A Grade*: The design you create has all the details correct, all elements selected supported by analysis (so the design can be scaled and also meets ISO 9000 requirements) and is ready for production....
   b. *B Grade*: you work for and are trusted by an “A grade” person, but you are not yet able to handle as much detail or as complex tasks as the “A grade” person.
   c. *C grade*: you should not have signed up for this course because you are not really focused and committed to it... you have lots of other things happening in your complex life...
4. Qualitatively grades in this class come from:
   a. For each of 12 weeks, each student will update their website with assignment elements (see below), and course staff/industry reviewers will comment on them with 5 (A+= wow!), 4 (A=great), 3 (B=ok), 2 (C=not impressed):
      i. Inherently cumulatively this will be the grade for the final project (see below) because all of the weekly assignments are heavily focused on helping you to create your final project!
   b. 50 point Final exam on FUNdAMENTALS of Design. Think of this as an interview for a job at Apple.... YES Prof Slocum has many former students who work at such companies and they have learned that grades are in general useless, so they conduct detailed technical interviews!
   c. In the end, students who want to contest their grade, may do so by bringing their final project and lab notebook to a meeting with course staff for an “interview” to assess do they really know the material in accordance with what they think their grade should be. Note, the grade change may then be up, or down.

**Learning Mechanisms**

1. Each week will have a *hardware* and a *brainware* component.
2. Beginning of course, select Term Project Machine that will be designed, built, and tested, where every assignment has application to the machine:
   a. Students must each *individually* design, build, and test their own entire machine: *The default theme for machines this semester is a computer controlled desk that can raise and lower so YOU can use it*
sitting down or standing! (search “rising desk” and look at images for examples):

i. Not everyone wants or needs a desktop machine, but most everyone wants a desktop!

ii. Students will design, build, and test their desk. Stiffness, accuracy, repeatability, and resolution will all be measured and compared to values predicted and then students will reflect to “close the loop on the design process” to see how well lessons have been learned.

iii. If a student has the experience and a compelling reason to undertake a different project please email Prof. Slocum before the class starts.

3. Students self-form 3 person peer review groups that are responsible for honest assessment of each other:
   a. There are no team projects but there are peer review teams!
   b. Part of a student’s grade is being able to provide (and receive) constructive and useful peer review to other students.
      i. Physics does not give a damn about your feelings or personal issues.

4. Assignments are created to help guide students with their term projects:
   a. Since students OWN their designs, very few handholding details (e.g., design specifications) for assignments will be given.
      i. An important part of this class is learning to be resourceful both in the shop and with your mind.
   b. Peer review will help students hone their ability to envision requirements

5. Each student MUST maintain a website of their peer-reviewed work on assignments/progress through the semester, which must be updated weekly:
   a. Instructors will review the websites to assess assignment performance.

6. Lab:
   a. A pre-requisite for the course is that each student **must** have their own access to a machine shop
      i. The default is the Hobby Shop and (for ME students) Maker Works.
      ii. Pending shop memberships will not be accepted.
   b. Students supply their own computer, control board, motor drivers, power supply, and motors (one stepper motor will be provided), because they get to keep their projects!
      i. If a student has financial issue with this, and cannot scrounge the parts from around MIT, please see Prof. Slocum for help.

7. Seek & Geek Exploration:
   a. Each week, students need to do one of the following:
      i. Take pictures of mechanisms or machines they find interesting or intriguing and take no more than a page to show the image and discuss: What is its function? What are the relevant
physics that engineers needed to consider? What questions or thoughts does it inspire in you
1. Post on your website!
2. This should take no more than an hour, and of course can be some mechanism you see that is related to or needed for your term project!

**Weekly Assignments:**
1. Below is a brief description of weekly assignments, which are to be completed, peer reviewed, edited/evolved as needed, and posted on students websites.
   a. The work assigned in a week is due by Sunday 6 AM of that week.
   b. Students have enough complexity with other courses, research... and Prof Slocum will grade Sunday morning while spinning and reviewing student’s websites with posted work
      i. Please keep font size readable for someone riding a bike (spinning)
   c. For the first 3 weeks the course staff will observe student website submissions
      i. Ideally, student websites and deliverables will improve through peer feedback and observing others’ work
      ii. A goal of the class is for students to learn to benchmark themselves against others – and be less dependent on specific feedback (because then has humans you can get dependent and passive)
   d. More specific feedback will then be given from week 4 onward

**Week 1:**
*Reading:* FUNdaMENTALS Topics 1, 2, 3, PMD Chapter 1
*Brainware:*
1. Create your website (if you have not already)
   a. It should have sections where you post your weekly Brainware and Hardware assignments
2. Create a one page “white paper” on the machine you will design, build, test this semester.
   a. State the problem to be solved, what else exists, and why you think you should design a new machine (even if just for fun)
   b. State the functional requirements and specifications for your machine, with the understanding that other than three stepper motors and the Arduino (or whatever you choose to use) control board and stepper motor drivers, each student has to scrounge up their own materials.
3. Design a simple planar exact constraint (EC) system to let a user explore sensitivities in fixturing a planar object
   a. You cannot just “print it”: you have to make it!
4. Seek & Geek Exploration

*Hardware:*
1. Make website for the work you will do in the course (it can be a new tab in your current personal website) and submit the URL to course staff
2. You should be able to demonstrate functioning of your Arduino board, power supply, and turn on a light, and ideally be moving a stepper motor (or get one this week from course staff and have it running by next week).

**Week 2:**
*Reading: FUNdaMENTALS Topics 4, 5, 6, PMD Chapter 2*
*Brainware:*
1. Start FRDPARRC table for your machine
   a. Identify dominant overall physics, references, risks
2. Deterministic design of a simple “precision” linear motion axis based on simple cheap elements (buildable from stuff you can obtain yourself (there is no budget or materials supplied):
   a. Structure, bearings, and carriage
      i. Make sure to leave room for the actuator!
      ii. Use spreadsheets to assign errors (error apportionment) and create preliminary error budgets for “best” concepts...
      iii. Use spreadsheets to analyze structural and machine elements you plan to use to ensure they can handle the loads...
      iv. You cannot just “print it”: you have to make it!
2. Seek & Geek Exploration
3. Update website

**Hardware:**
1. Make sure your arduino can control your stepper motors!
   a. Ask teammates for help if needed. Be resourceful and interact with your peers!
2. Make your planar exact constraint (EC) system from materials you can obtain yourself and get together with your peer group to play with each other’s systems and discuss.
   a. This simple device is something to keep and cherish, and bring to interviews....

**Week 3**
*Reading: FUNdaMENTALS Topics 7, 8, PMD Chapter 3, 4*
*Brainware:*
1. Evolve your linear motion axis design and make part drawings.
   a. Design in where the actuator will go
2. Create solution strategies for your machine
   a. Stick figures
   b. FRDPARRC table for each strategy
   c. Use the error apportionment spreadsheet
   d. Model 1st order loads, stiffness requirements
   e. Geometric error budgets for “top” strategies
3. Seek & Geek Exploration
4. Update website

**Hardware:**
1. Make and test your linear motion system (does not have to include actuator).
   a. Use a mounted laser pointer to test and record change in position on piece of paper placed far away

**Week 4**

Reading: FUNdaMENTALS Topics 9, 10, PMD Chapter 5, 6

**Brainware:**
1. Based on last week's results, evolve linear motion system design (if needed) so this week you can mount and test the actuator
2. Design (use the spreadsheet) a three groove kinematic coupling to couple anything you want (see web.mit.edu/2.75 for examples)
3. Ruminate, play, evolve, and pick “best” strategy for machine
4. Seek & Geek Exploration
5. Update website

**Hardware:**
1. Modify the linear motion system as needed so you can mount and test the actuator in the system.
   a. Use a laser pointer mounted to it and record change in position on piece of paper placed far away
   b. How do results differ from last week?
2. Make your kinematic coupling and use a laser pointer attached to it that projects down the hall to measure repeatability.

**Week 5**

Reading: PMD Chapter 7

**Brainware:**
1. Continue to evolve your linear motion system spreadsheets to predict performance.
   a. This is closing the loop on your designs and helps to build design intuition
2. Layout concepts for the full machine
   a. Create stick figures for concepts
   b. Assign errors (error apportionment) and create preliminary error budgets for “best” concepts
   c. Make sure to DESIGN it (write the spreadsheet—predict performance and size elements)
3. Design a simple system to test at least one idea you plan to use to preload bearings and actuators to eliminate backlash in your machine's bearings
   a. Make sure to DESIGN it (write the spreadsheet—predict performance and size elements)
4. Seek & Geek Exploration
5. Update website

Hardware:
1. Make sketch models (foam core and/or wood) of your top concepts to get a feel for the performance, errors, etc.

Week 6
Reading: PMD Chapter 8
Brainware:
1. Based on last week's hardware tests, evolve your full machine concepts
   a. Select at most three top designs
   b. Complete the geometric error budgets for each
   c. Pick the “best” design to move forward with design details
2. Upgrade the error budget to include stiffness of elements
3. Seek & Geek Exploration
4. Update website

Hardware:
1. Make and play with your bearing backlash elimination device and your actuator backlash elimination device
2. Further sketch modeling if needed for a quick test of an idea

Week 7
Reading: PMD Chapter 9, 10
Brainware:
1. Evolve your design as needed
   a. Update error budget
   b. Update design spreadsheets you have created or used
2. Complete detailed design of Most Critical Module (MCM)
   a. Design spreadsheets...
   b. Part drawings, and BOM so you can start building after or during spring break
3. Create solid model of your entire machine, showing all critical details
   a. Preliminary selection of bearings and actuators and structural sections
      i. Use spreadsheets to verify design/selection of all machine elements
   b. You do not need to include bolts or fillets and chamfers... unless they are critical features
4. Seek & Geek Exploration
5. Update website

Hardware:
1. Further sketch modeling if needed for a quick test of an idea

Week 8 SPRING BREAK (or catch up time!)
Brainware:
1. RELAX – go for a run, exercise is good for the psyche 😊
2. THINK and REFLECT on the first 7 weeks of class
   a. Make changes to your machine you think are needed

Hardware:
1. Take care of yourself!
2. Obtain materials you will need for building your machine

Week 9
Brainware:
1. Complete detailed design of remaining modules
   a. Design spreadsheets...
   b. Part drawings, and BOM
2. Seek & Geek Exploration
3. Update website

Hardware:
1. Build and test MCM
   a. This should include an actuator, and make sure your computer can control the motion of your MCM
   b. Measure performance and compare to predicted performance
   c. Load capacity, stiffness, accuracy, repeatability, resolution

Week 10
Brainware:
1. Updates to models as needed based on build and test activities
2. Document the design of the machine
3. Seek & Geek Exploration
4. Update website

Hardware:
1. Build and test remaining modules

Week 11
Brainware:
1. Updates to models as needed based on build and test activities
2. Continue to document the design of the machine
3. Seek & Geek Exploration
4. Update website

Hardware:
1. Build and test remaining modules

Week 12
Brainware:
1. Updates to models as needed based on build and test activities
2. Continue to document the design of the machine
3. Seek & Geek Exploration
4. Update website

**Hardware:**
1. Integrate modules and test, modify

**Week 13**

**Brainware:**
1. Updates to models as needed based on build and test activities
2. Finish document on the design of the machine
3. Begin presentation on the design, build, test of the machine
4. Seek & Geek Exploration
5. Update website

**Hardware:**
2. Complete tests and modifications

**Week 14**

**Brainware:**
1. Finish presentation on the design, build, test of the machine
2. Seek & Geek Exploration
3. Make sure website up to date

**Hardware:**
3. Test, modify
4. Celebrate!

**Week 15**

**Brainware:**
1. Final Exam during finals period
   a. If you deterministically designed your machine during the semester, you should be great on the final!
      i. The questions will mostly be written about machine design aspects of the desk design!
         1. Stiffness, accuracy, constraints... (you know, FUNdaMENTALS! 😊)