Teaching Dynamic Systems and Control without Dynamics

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Abstract

This work-in-progress paper explores whether or not it is possible to teach dynamic systems and control effectively to students who do not take dynamics. Grand Valley State University offers two different versions of a junior-level dynamic systems and control course. One version is for mechanical engineering majors and requires dynamics as a prerequisite; the other version is for Product Design and Manufacturing Engineering (PDM) majors and does not have dynamics as a prerequisite. Learning outcomes are compared for students from these two different courses through common final exam questions and a common lab activity. This paper presents a baseline assessment of whether or not students who do not take dynamics can develop a solid understanding of the dynamics of under-damped, second-order systems along with a preliminary investigation into the effectiveness of several strategies for teaching dynamic systems. This paper also presents results from an online survey regarding how the course affected students' attitudes towards computer programming and their assessment of their programming skills.

Introduction and Background

This work-in-progress paper provides both a bench mark and an assessment of initial strategies for teaching dynamic systems and control to students who do not take dynamics. The bench mark is done by comparing student learning outcomes between two different versions of a junior-level dynamic systems and control course: one that has dynamics as a prerequisite and one that does not.

The Product Design and Manufacturing Engineering (PDM) program at Grand Valley State University is a hybrid between mechanical and manufacturing engineering with an emphasis on design and new product development. Because of the challenges of fitting in all of the desired content, students in the PDM program do not take dynamics. The prerequisites for the PDM version of the dynamic systems and control course are physics and differential equations.

System dynamics can still be challenging even to students who did well in dynamics and not all of the concepts taught in dynamics are essential for system dynamics [1,2]. However, certain topics, such as finding the transfer function for mass/spring/damper systems will come easier to students who have taken dynamics.

A conglomeration of teaching strategies was used to grow students' understanding of dynamic systems with a particular emphasis on under-damped, second-order systems. The strategies employed included supplemental and semi-flipped instruction, online learning modules, experimental in-class demonstrations, and hands-on physical experiments.

Pedagogical Research Questions

The primary question this paper seeks to investigate is whether or not dynamic systems can be taught effectively to students who do not take dynamics. A secondary question is whether or not there is a difference in students' attitudes or self-efficacy related to programming tasks associated with dynamic systems and control if they use Python and the Jupyter notebook interface as opposed to Matlab®.

Literature Review

Dynamic systems and control courses can be abstract, mathematically intensive, and difficult to teach. Educators and researchers have taken many approaches to solving this problem. Physical experiments have been shown to have significant pedagogical value[3,4,5,6,7]. The equipment costs, space requirements, and other challenges of university-owned control laboratories has sparked considerable interest in student-owned control experiments[8,9,10]. The focus on student-owned control experiments has lead to many novel platforms such a small robotic vehicle with a custom micro-controller board[11] and a 3D printed experiment for balancing a ball on a plate[12]. Other instructors have used extensive simulations[13] and haptics[14] to enrich dynamic systems and control courses.

The abundance of online videos on control-related topics along with the relative ease with which instructors can create and distribute their own lecture videos has brought into question how to best use face-to-face instruction time. One answer to this question is to "flip" the course by having the students watch the lecture ahead of time and then use class time for extensive examples or active learning activities. Flipped instruction can be particularly helpful in control-related courses by ensuring that students still receive adequate instruction in control theory while making time for challenging experimental projects. As reported by de la Croix and Egerstedt, students who are given challenging projects but not enough instruction in control theory often create complex control algorithms that are not sound[15]. Conversely, students who receive control theory but are not given experimental projects often have a difficult time implementing the theory they have learned.

Flipped instruction can be particularly powerful when augmented by low-cost, easy-to-implement experiments. A key challenge in developing appropriate experiments is keeping the cost down while keeping the students from getting lost in implementation details. Hill designed and

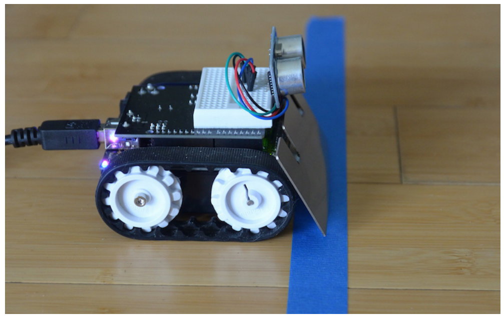

Figure 1: Picture of the Zumo robot chassis and sonar sensor along with a masking tape stopping line

presented a series of such experiments that combined an Arduino micro-controller board with Matlab and used them in a flipped dynamic systems and control course[16].

Pedagogical Innovations

On some level, this paper serves as a benchmark to see how well PDM students who do not take dynamics understand system dynamics and control compared to ME students who do take dynamics as a prerequisite. Additionally, this paper investigates the effectiveness of some initial pedagogical innovations for teaching system dynamics and control. The pedagogical innovations are described next.

Introductory Demonstration

A first day lecture/demo was designed for the PDM version of the course to motivate the students and lay a foundation for their learning. Because PDM students do not take dynamics, it seemed especially important to help them understand what is meant by the terms "dynamic systems" and "control."

The demo uses an Arduino-based Zumo robot chassis and a sonar sensor. The entire system costs roughly $125. The goal is to get the robot to stop at a prescribed distance form a wall as shown in Figure 1. To start a test, the robot is pulled back from the line and a command is given using the Arduino serial monitor. Initially a simple on/off control is used that turns the motors off when the robot reaches the line. Not surprisingly, the robot coasts past the stopping line, leading to a discussion of inertia and how to account for it in modeling the system. Students are then asked how to improve the system and the discussion is guided toward using the sonar to determine the motor speed. At some point proportional control is attempted. Test results for proportional control are shown in Figure 2. The demonstration is easy to perform in class, requires only the free Arduino software, and illustrates the essential components of a feedback control system. Assessment of the effectiveness of the demo will be presented later in the paper.

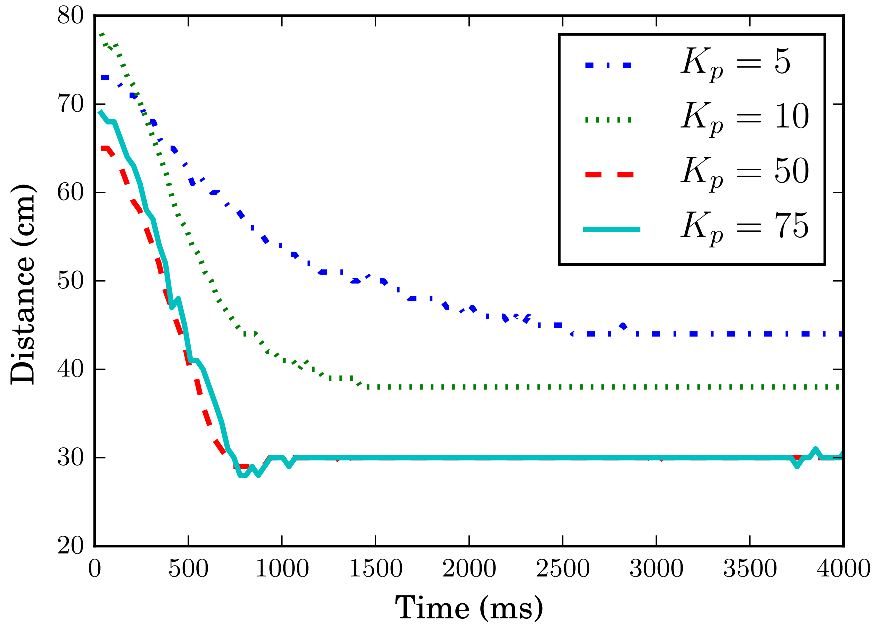

Figure 2: Proportional control test results for the sonar robot car with various values for K_p and a desired stopping point of 30cm from the wall

Semi-Flipped Instruction and Review Videos

Online lecture videos were used in the PDM section of the course. Because of the timing of when the videos were developed and published online, they did not lead to truly flipped lectures. The videos provided more review content than anything else. However, it is believed that each student watched the review videos at least once before the midterm since the number of views of each video exceeded the number of students in the class shortly after the videos were uploaded.

Without any prompting from the instructor, two different students commented on their course evaluations that the class should be taught in a flipped format. In response to this, an online survey was created and 64% of the respondents said that most of lectures should be flipped and 9% said that all of the lectures should be flipped. Flipped lectures will be incorporated to a greater extent in the next offering of the course.

Lab Activities

Both versions of the course include a lab, however the lab content is not identical between the versions. Many of the labs for the PDM version of the course used a DC motor/encoder system, shown in Figure 3. The motor is driven by an H-bridge chip connected to either a battery pack or a power supply. An Arduino Uno is used to read the encoder signals, perform control calculations, ensure the real-time execution of the controller, and send a PWM signal to the H-bridge. The Arduino prints delimited ASCII data to the serial monitor which can then be copied and pasted into a text editor or spreadsheet program for plotting and data analysis, such as comparison with simulations. The Arduino software is all that is needed to run real-time

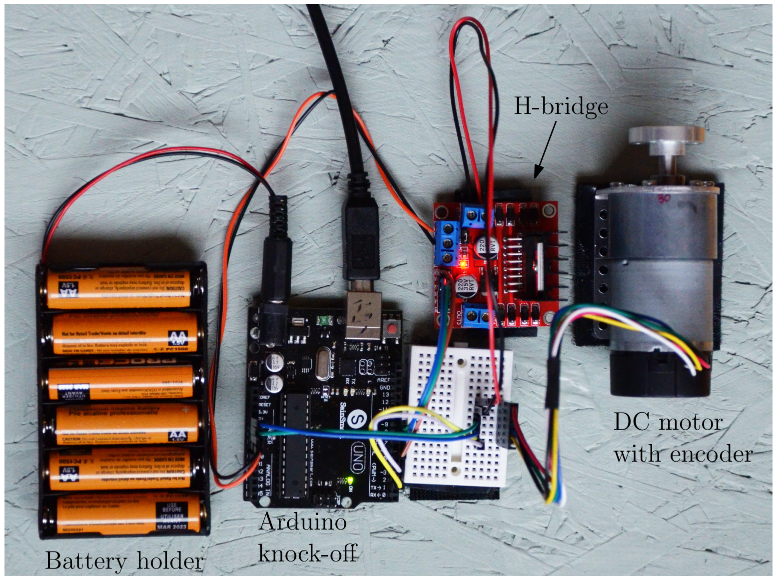

Figure 3: The DC Motor/Encoder/H-Bridge system used for many labs in the PDM version of the course and in the common root locus lab activity.

experiments and collect data.

The DC motor system can be used for at least 6 active learning experiments:

1. Using interrupts to decode the encoder signals
2. Identifying and compensating for deadband
3. Time-domain system identification
4. PID tuning
5. Root locus control design
6. Frequency response

The DC motor system may seem simple to instructors with considerable experimental expertise, but students or faculty with little experience can assemble it and a lot can be learned from it. The experimental system can be constructed for roughly $75 per lab station. The cost and source of the components are listed in Table 1.

Additionally, 3D printed flexible beams with low-cost accelerometers were attached to the DC motors in a frequency response lab. Some lab groups were able to produce Bode plots for this lab, but this activity needs to be refined before the next offering of the course.

Using the Python-Control Module to Verify Inverse Laplace Analysis

It seemed like students in the PDM section were struggling with initial Laplace theory early in the course. In order to combat this, the instructor created a tutorial and online video on how to use the

Table 1: Cost and source of the components of the DC Motor/Encoder system

Item	Source	Cost
DC Motor with Encoder	pololu.com	$37
Motor Mounting Bracket	pololu.com	$4
H-Bridge	amazon.com	$7
Power Supply (2A 5V)	amazon.com	$11
Uno Knock-Off	amazon.com	$11
Breadboard and Jumper Wires	amazon.com	$5

`impulse_response` method of the Python control module to numerically verify the solution to any inverse Laplace problem. To help the students prepare for the midterm, each student was required to make up their own inverse Laplace or differential equation problem and then post the solution along with the numeric verification. Their solution would most likely be worked out by hand. This approach lead to 20 practice problems being created just before the midterm and seem to help students finally get comfortable with Laplace analysis, especially partial fraction expansion and inverse Laplace.

Bode and Root Locus random problem generators

A final innovation involved using Python to help students prepare for the final exam. The instructor created Python code to intelligently generate random root locus and Bode practice problems. The random problem generators were intelligent in the sense that the code tries to generate "good" transfer functions for the problems rather than simply generating a purely random transfer function.

Both random transfer function generators produce strictly proper transfer functions. The root locus generator produces transfer functions with at most one pair of complex conjugate poles and up to five total poles. At most one unstable pole is allowed. Only real zeros are allowed. These constraints can be adjusted to suit the preferences of the instructor.

In order to help students who are learning Bode plots for the first time, it is helpful if the poles and zeros are spaced out fairly well. To this end, the Bode generator separates the frequency range into decades, and no decade is allowed to have both poles and zeros. Each decade can have either one real pole or zero or one complex conjugate pair of poles or zeros. It is also possible for a decade not to have any poles or zeros.

The random Bode problem generator can be used in two ways:

1. The student can allow the code to show them the transfer function and then they would sketch the corresponding Bode plot.
2. The student can have the code generate the Bode plot without showing them the transfer function and they can estimate the transfer function based on the Bode plot (i.e. system identification).

Assessment Approach and Results

The benchmark and assessment presented in this paper was done by comparing student learning outcomes between the two versions of the course (PDM and ME) through common final exam questions, a common root locus laboratory assignment, surveys related to the introductory demonstration, and a survey comparison of students' attitudes toward programming.

The mechanical engineering (ME) section that has dynamics as a prerequisite is assumed to be an example of a typical dynamics systems and control course. If students who do not take dynamics can achieve the same depth of understanding of system dynamics as the ME students, then this work would be considered successful.

First Day Demo Assessment

The effectiveness of the first day lecture/demo was assessed in two ways. First, the students where given a live poll at the start and end of the first lecture asking them how enthused they are about the course. This was done using `directpoll.com` and the students respond on their phones, tablets, or laptops. The results are shown in Figure 4. Additionally, the students were given an online survey before and after the first day lecture/demo asking them to define the terms "dynamic systems" and "control." The occurrence of various keywords in the students' answers to the questions are summarized in Figures 5 and 6. The students' definitions are vague before the first day lecture/demo and get more specific after. In the discussion following the demo, it was pointed out that for mechanical systems, Newton's second law is key and both acceleration and mass need to be non-zero for a system to be considered dynamic. Note that 21 students completed the survey in the PDM course.

The online survey was also given to the ME students after two weeks of lecture. The students in the ME section did not see the demonstration and the instructor of that section did not explicitly lecture on the definitions of dynamic systems and control. It seems like students who saw the demo have a more concrete idea of what a dynamic system is than those who did not see it.

Common Exam Questions

Four of the final exam questions were common. Each instructor also added some additional questions that were specific to their version. There were 20 students enrolled in the PDM version of the course. One section containing 26 students from the ME version was selected for assessment. It should be noted that questions 2 and 3 essentially ask the students to work backwards compared to the problems assigned in homework or done as in-class examples. None of the instructors had asked the students to do problems like questions 2 and 3 prior to the final exam.

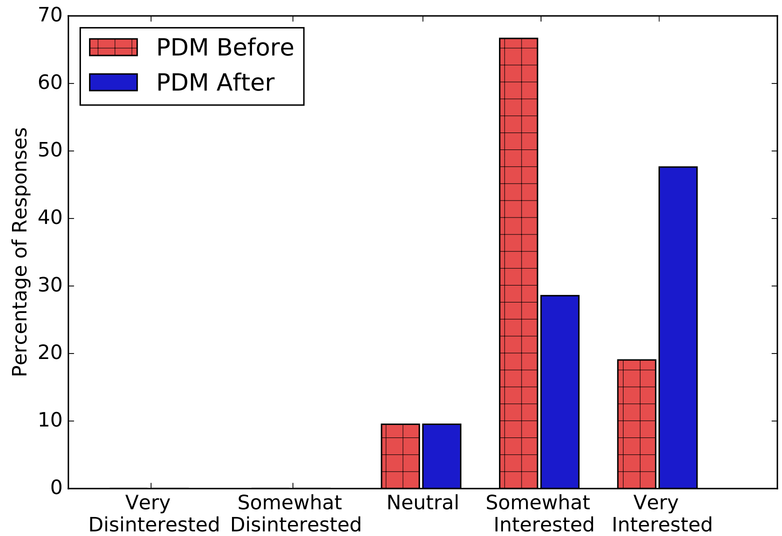

Figure 4: Bar graph of student responses concerning their interest in the course before and after the first day demo/lecture

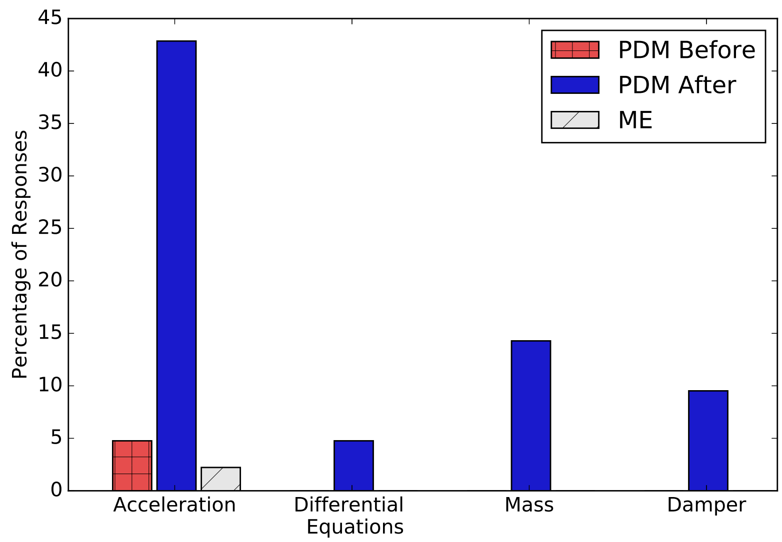

Figure 5: Bar graph of the occurrence of keywords in students' responses to the question "What is a dynamic system?".

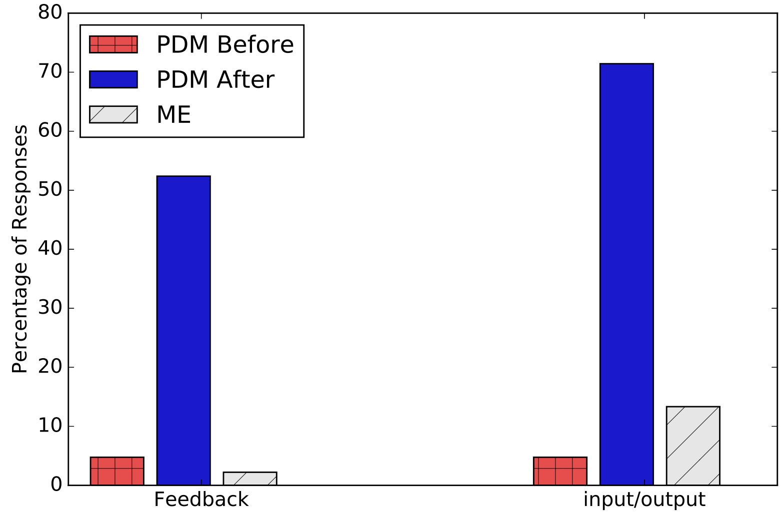

Figure 6: Bar graph of the occurrence of keywords in students' responses to the question "In this class, what do we mean by the word 'control'?".

Question 1

Question 1 assesses students' understanding of the relationship between pole locations and step responses for second-order systems. Two of the systems are under-damped and two are over-damped. Students are asked to match the step responses shown in Figure 7 to the pole locations shown in Figure 8. Students are also asked to supply the reasoning behind their choices.

Question 1 Problem Statement

- Match the systems 1-4 with their step responses a-d and provide the reasoning for your choices.
  - **Note that Figures 7 and 8 were** printed directly below the problem statement on the exam.

Question 1 Assessment Figure 9 shows the percentage of ME and PDM students correctly matching the systems with their step responses. The under-damped and over-damped systems were grouped together in the assessment. Students in both groups handled the under-damped systems very well. The over-damped systems proved to be more challenging, particularly for PDM students. So, understanding over-damped systems is an area for improvement in the next offering of the PDM version of the course.

The reasoning given for the students' choice for the over-damped systems also showed differences between the two versions of the course. Thirty one percent of ME students mentioned that system 3 has the slowest pole, while none of the PDM students mentioned this. PDM students who correctly matched the over-damped systems mentioned that system 3 has higher

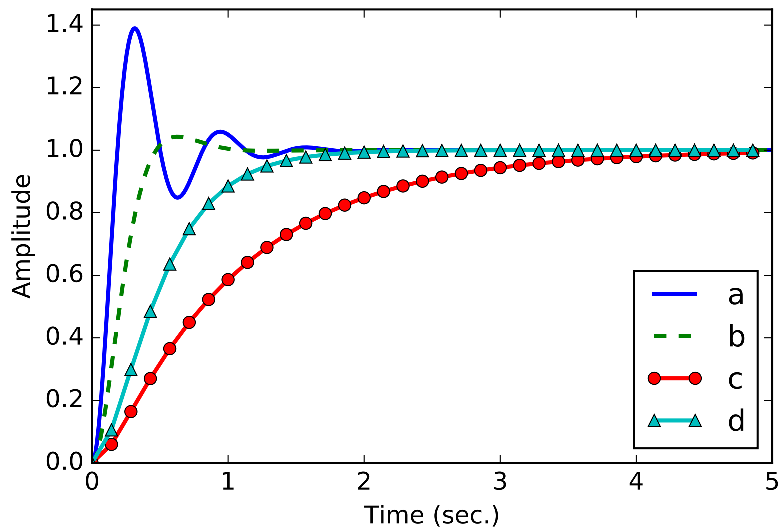

Figure 7: Step responses of the systems for problem 1 to be matched with the pole locations shown in Figure 8

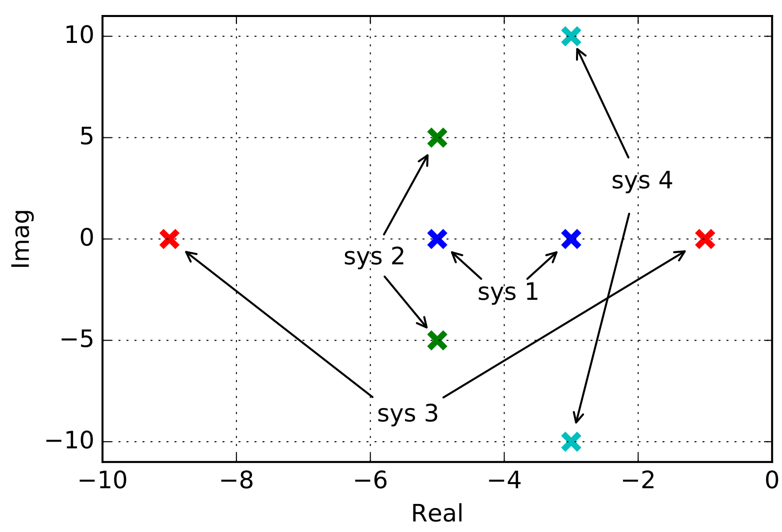

Figure 8: Pole locations for the systems for problem 1 to be matched with the pole locations show in Figure 7

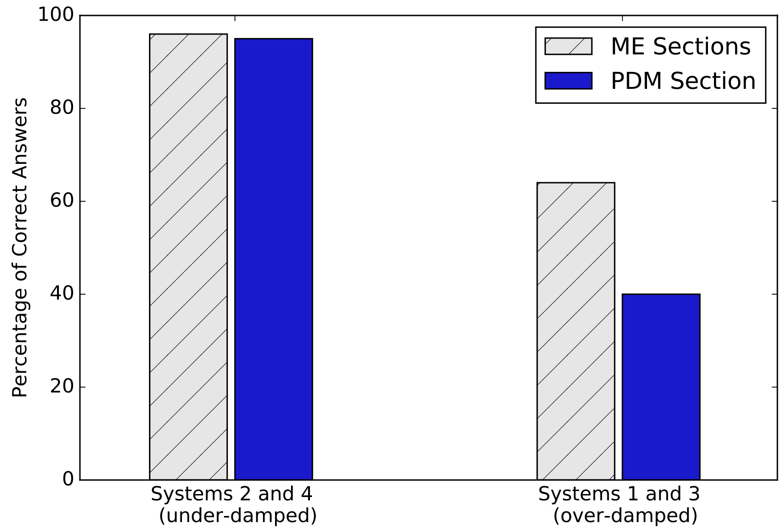

Figure 9: Bar graph for final exam question 1

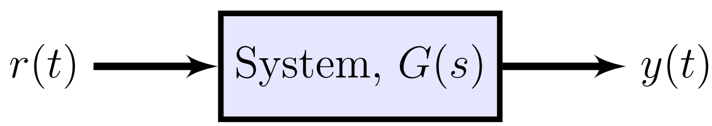

Figure 10: Input/output black box for Question 2

damping than system 1. While this is true in some sense, it reflects less understanding than talking about which first order pole is slowest.

Question 2

Question 2 is a bit of a philosophical one that probes the students understanding of the definition of a transfer function. Students are given time domain expressions of the input and output of a system and asked to find the transfer function. If students remember that a transfer function is the Laplace transform of the output divided by the Laplace transform of the input, this problem should be fairly straight forward. Ideally, students will also remember the instructors' preferences that a transfer function be given as a proper fraction with one polynomial of s in the numerator and one polynomial in the denominator.

Question 2 Problem Statement

- **You are given a black box and are required to find out its transfer** function (see Figure 10). If a step input, $r(t) = 1$ for $t > 0$, is supplied to the system, the output signal is $y(t) = t - (1/3)\sin(3t)$.
- The initial conditions are zero. Determine the transfer function.

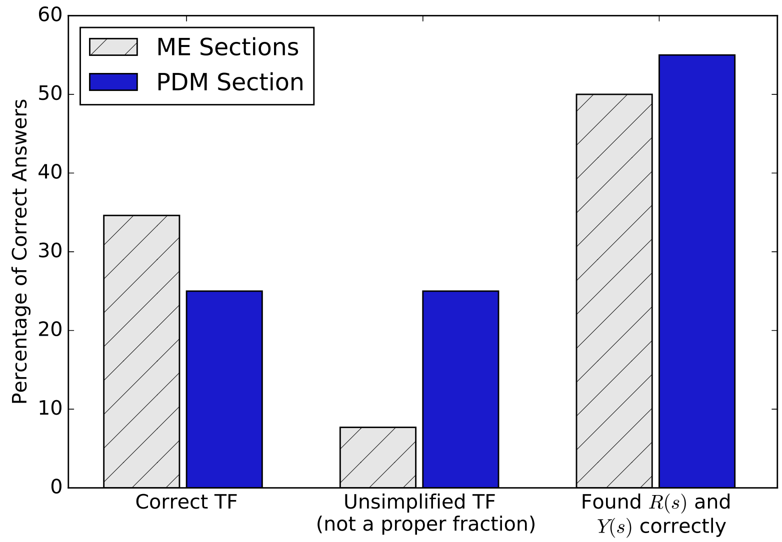

Figure 11: Bar graph for final exam question 2

Question 2 Assessment The percentage of each section correctly finding the transfer function and correctly finding the Laplace transform of input and output is shown in Figure 11. Interestingly, 8 out of 20 of the PDM students tried to infer the transfer function from some form of reverse partial fraction expansion. This approach could be interpreted as either creative problem solving or simply trying to use the main Laplace approach (partial fraction expansion) on a problem where it does not really fit. No ME students attempted this approach.

This seems to be a fairly challenging conceptual problem if the students have never been asked a question like this.

Question 3

Question 3 asks students to interpret a root locus. In the homework and lab activities, students have been asked to sketch root loci or generate them using a computer. Before the final exam, students had not been asked to find the transfer function from a root locus nor had they been directly asked the kind of interpretation questions that were on the final exam.

Question 3 Problem Statement

- Given the root locus shown in Figure 12:
  a. Find the associated loop transfer function $\hat{G}$.
  b. Identify the portions of the root locus where the system has oscillatory roots.
  c. Will this system be stable for all choices of gain K? If not, identify the portions of the root locus where the system becomes unstable.

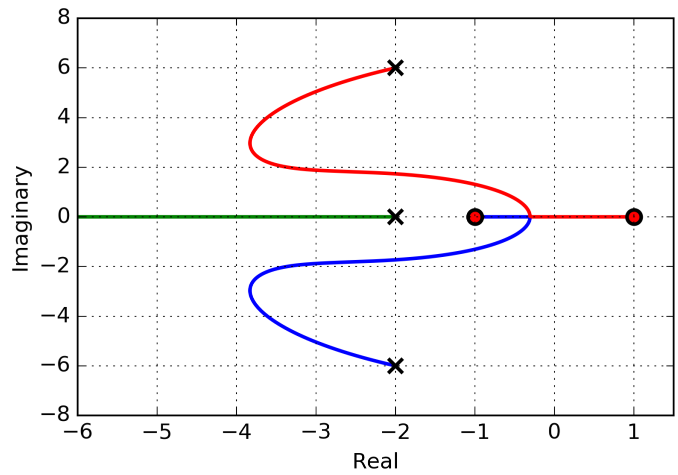

Figure 12: Root locus for final exam Question 3

d. Is it possible for this system to have a stable, non-oscillatory response? If so, identify where the dominant poles would be for such a response.

Question 3 Assessment The percentage of each section that gave correct answers for parts a-d are shown in Figure 13.

Both ME and PDM students worked on a common root locus lab activity. It is worth noting that PDM students received several lectures and had one homework assignment in addition to the lab. ME students received instruction through a pre-lab lecture and several YouTube videos, but root locus was not explicitly covered during the ME lecture portion of the course. So, it is slightly disappointing that PDM students did not out perform ME students on this portion of the final exam.

So far, no effort has been made to determine if the ME population is actually stronger theoretically than the PDM population. This could be done through comparing cumulative GPAs or average calculus and physics grades. It is certainly possible that students who successfully complete dynamics have stronger analytical skills than students who do not. Faculty in the PDM program hope that students choose the PDM major based on an interest in product design and manufacturing, but it is certainly possible that some choose the program to avoid dynamics and other more theoretical and analytical courses.

Question 4

The fourth and final common exam question is a two degree of freedom modeling question with one small wrinkle: the input is a displacement rather than a force. If the students draw the necessary free body diagrams and carefully ask themselves what the differential displacements are for each spring and what the differential velocities are for each damper, it should be fairly straightforward to find the transfer function that the question asks for.

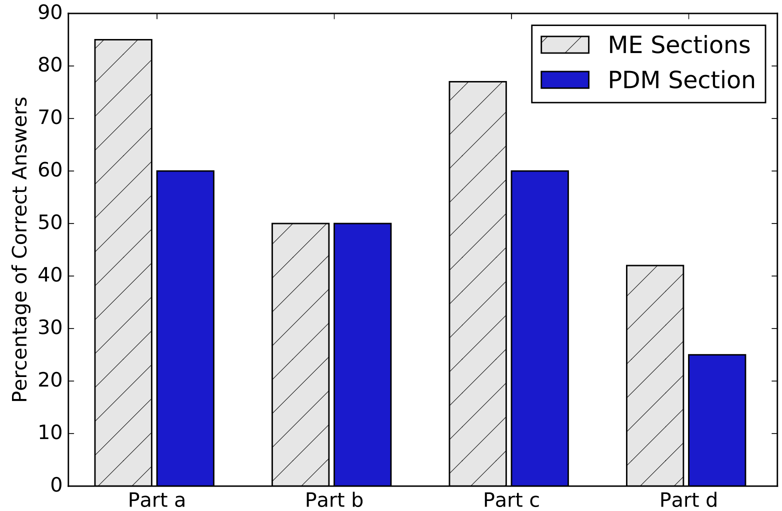

Figure 13: Bar graph for final exam question 3

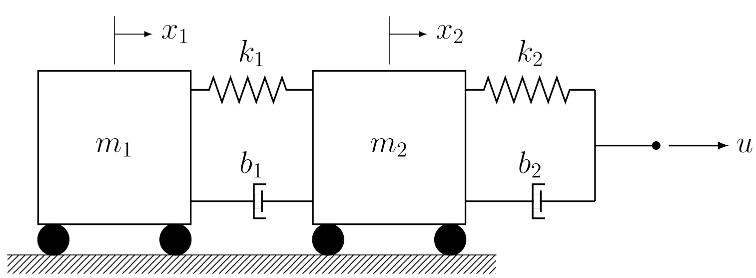

Figure 14: Schematic for the mass/spring/damper modeling problem (Question 4)

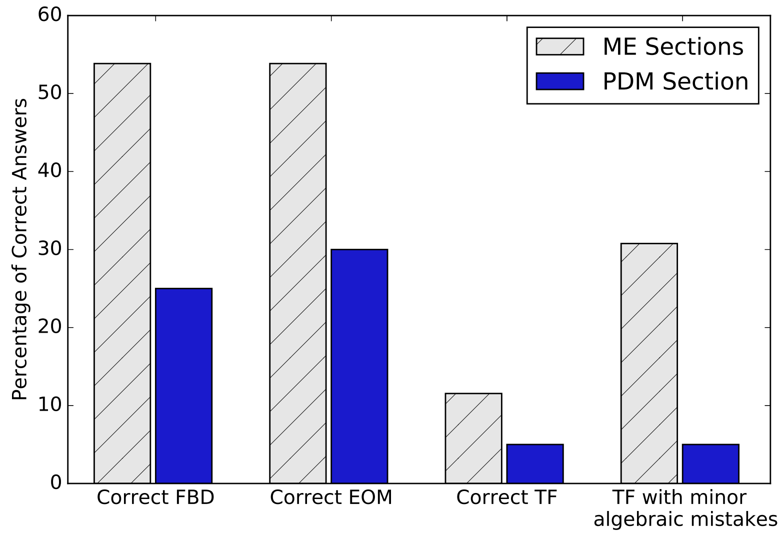

Figure 15: Bar graph for final exam question 4

Question 4 Problem Statement

- **Find the transfer function for the system shown above** (Figure 14) with displacement input u and output x_2.

Question 4 Assessment The ME students handled the displacement wrinkle better than the PDM students, but it still tripped up a decent percentage of students. The percentage of each section that drew correct free body diagrams, wrote correct equations of motion, and came up with the correct transfer function is shown in Figure 15.

Clearly, modeling is more challenging for PDM students than for ME students; this makes sense given that FBDs and EOMs are core topics in dynamics.

The prerequisite quiz given on the first day has a very straight-forward, single-degree-of-freedom mass/spring/damper problem on it. Only one student in the PDM section drew a correct FBD and none of the students got the EOM right. So, even though the performance on the modeling question on the final exam is fairly bad, it is still an improvement over the prereq quiz.

Common Laboratory Assignment

A common final laboratory assignment was also used to compare learning outcomes between the ME and PDM sections of the course. The lab asked students to use a root locus approach to design P and PD controllers for the DC motor/encoder/H-bridge system discussed earlier in this paper. Students were asked to choose control gains that would lead to lightly damped, heavily damped, and over-damped responses. They were also asked to simulate the step response of their closed-loop systems and to compare the simulations with experimental results. They were also asked to discuss whether or not the experimental step responses made sense given the corresponding pole locations on the root locus.

The assignment assesses student understanding of root locus design, the relationships between pole locations and step responses, and how to perform closed-loop simulations. All of these are core concepts in dynamic systems and control. This approach could be valuable to any program interested in assessing its students understanding of dynamic systems and control.

While this approach shows promise as a standardized dynamic systems and control assessment tool, the first attempt at Grand Valley State University was not successful. The ME lab sections did not initially use the exact same hardware as the PDM section. Additionally, the assignment came at the very end of the course and the students seemed rushed and possibly worn out. Many of the groups turned in lab reports of lower quality than the work they had done earlier in the semester. In the end, it was not possible to perform a meaningful comparison between the ME and PDM sections. This assessment will likely be re-attempted when the courses are offered again next fall.

Programming Attitudes Survey

One additional comparison was made between the ME and PDM sections of the dynamic systems and control course: an online survey asked students how their attitude toward programming and their perception of their programming ability had changed from the beginning to the end of the course.

Computer programming plays a valuable role in dynamic systems and control courses. Tools like Matlab or Python can be used to generate root loci and Bode plots, to simulate the responses of systems, and to analyze experimental data. The ME sections of the course used Matlab while the PDM section used Python along with the python-control module and the Jupyter notebook. The Jupyter notebook provides a web interface that allows students to type code into cells and then see any results immediately in an output cell. The notebook merges the traditional editor and command line into one interwoven interface, providing students immediate feedback on each chunk of code they enter. Additionally, plots can be shown immediately following the cells that generates them, making it easier to associate the figure with the corresponding code.

In addition to Matlab or Python, both PDM and ME students used C to program their Arduinos for lab activities.

Figures 16 and 17 compare responses between the ME and PDM sections of the course to the two most pertinent survey questions. Note that the number of responses is too small to claim statistical significance: 20 out of 85 MEs responded to the survey and 13 out of 20 PDM majors responded.

Figure 16 compares responses to the question "How has your attitude toward programming changed from the beginning of this course?" A larger percentage of PDM students than ME students enjoy programming more at the end of the course than they did at the beginning.

Figure 17 compares responses to the question "Have your programming skills improved since the beginning of this course?" A larger percentage of PDM students than ME students feel like they are better at programming now. Self-efficacy related to programming is of some value, but it

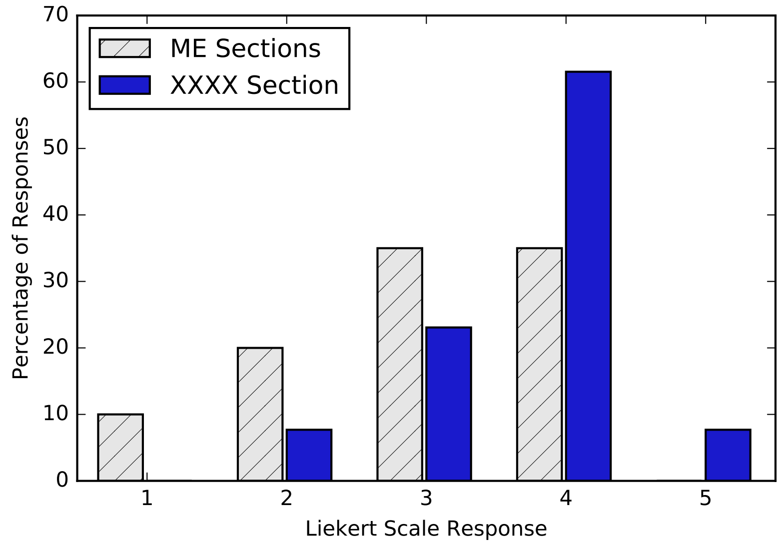

Figure 16: Comparison of student answers to the programming attitudes survey question: How has your attitude toward programming changed from the beginning of this course? Liekert scale options: 1: I dislike programming much more now. 2: I dislike programming a bit more now. 3: My feelings have not changed. 4: I enjoy programming a little more now. 5: I enjoy programming much more now.

would be beneficial to supplement this in the future with some objective assessment of students' programming skills related to dynamic systems and control.

Conclusions and Future Work

Students from the ME version of the dynamic systems and control course outperformed their counter parts in the PDM version on nearly all aspects of the common final exam questions. The assessment data provides a valuable benchmark and shows faculty in the PDM program areas for improvement.

Several first attempts at pedagogical innovation related to teaching dynamic systems and control were also presented, including an effective introductory demonstration and a low-cost experiential system that can be used for 6 or more lab assignments. Additionally, a lab procedure was presented that could be used for widespread assessment of dynamic systems and control learning.

Survey results show that using Python, the python-control module, and the Jupyter notebook were well received by PDM students.

Given the different emphases of various engineering programs and the make up of different student populations, it may not be an appropriate goal to have manufacturing students understand the dynamics of second-order systems to the same depth as ME students. However, knowing how manufacturing students compare to MEs in this area may still provide valuable data to guide manufacturing programs in their curriculum choices.

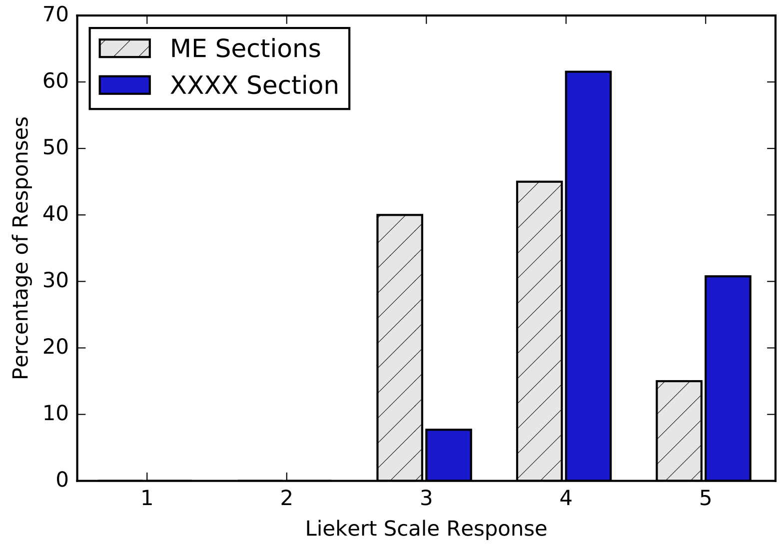

Figure 17: Comparison of student answers to the programming attitudes survey question: Have your programming skills improved since the beginning of this course? Liekert scale options: 1: I am much worse at programming than I was at the beginning of the course.; 2: I am somewhat worse at programming than at the beginning of the course.; 3: My programming skills have not improved at all through this course.; 4: I am somewhat better at programming now than at the beginning of the course.; 5: I am much better at programming now than at the beginning of the course.

Future work will include a more carefully constructed first day quiz so that better pre/post assessment can be done between the quiz and the final exam. Additionally, the root locus lab will be run again with all groups using identical hardware. An investigation will be made into why some students were not able to generate Bode plots for the 3D printed beam frequency response, so that the lab activity can be redesigned. Finally, faculty from other institutions will be recruited so that small, initial steps toward something like the Dynamics Concept Inventory can be created for dynamic systems and control[2].

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