Integrating Education in Mathematics, Physical Science, Engineering Science and Application in a Required Course

Dale E. Schinstock
Kansas State University

Introduction

This paper addresses a common problematic scenario in engineering education through a specific example of the overhaul of a required course in a mechanical engineering curriculum. The course was designed with three major themes in mind: 1) often, less is more in the context of the topical coverage and retention and understanding, 2) application of material and active learning are important motivating factors for the students, and 3) moving engineering application to earlier in the curriculum engages the students in the curriculum. The problematic scenario addressed is as follows. In a typical mechanical engineering curriculum a first course in control systems is taken in the senior year with prerequisites of differential equations, calculus based physics and dynamics, and frequently another course beyond dynamics that focuses on the modeling of dynamic systems using differential equations. Even with these prerequisites and at this advanced stage of the curriculum, this course often never gets to true engineering application of the material. Still, students somehow feel overwhelmed by the amount of material covered in the course and feel as though the carrot of application is still dangling in front of them. Although the scenario above focuses on the control systems area, it is common in many advanced topics in engineering. By integrating the learning of advanced mathematics, engineering science, and engineering application into a single course earlier in the curriculum the actual amount of material learned is increased. This does however require the reduction of specific topical coverage in any one of the single areas.

The course described here is a first course dealing with feedback control systems, which is frequently a required course in mechanical, electrical, and aerospace engineering programs. It is typically taken in the senior year of such programs. In our program, the course is a required lecture/laboratory scheduled to be taken in the junior year of the Mechanical Engineering program. It is a four credit hour course with lecture and lab. It has prerequisites of differential equations, dynamics, and computer programming. As the result of a curriculum reform effort within the department this course replaced a course focused on the modeling of dynamic systems that was a prerequisite for the control systems course at that time. While this modeling course covered topics in great depth and breadth, it had very little real engineering application.

A high-level outline of the topical coverage of the course follows.

- Introduction (1 week)
- Solution of differential equations with Laplace transforms and modeling of electromechanical systems with transfer functions and block diagrams (5 weeks)
- Detailed treatment of transient response with 1st order systems, 2nd order systems, and systems multiple poles and zeros (2.5 weeks)
- Root locus as a qualitative (i.e. without actual gain calculations) design tool (1 week)

- Frequency response analysis and design (2.5 weeks)
- Pulling things together and tuning of control systems (1.5 weeks)
- Exams (1.5 weeks)

Aside from moving engineering application to earlier in the curriculum, several of aspects of this course are important to the learning of the students. We have redesigned the laboratory for the course. The lecture, lab, and homework coalesce the topics of course throughout the semester. The course reduces the specific topical coverage while increasing expectations for greater understanding of the topics covered. In addition, it focuses on a few key concepts used throughout the semester to tie the topics together.

This course has been a great success story. From the author's experience of teaching at three different universities, this required course is usually despised by a majority of mechanical engineering students. Now that these course changes have been implemented, student interest is at an all time high and their praise for the course is abundant.

Description of the Laboratory

The laboratory is an important part of the course. Each student attends a weekly laboratory. The students work in pairs and turn in a weekly lab report. In most cases, the reports are informal, with emphasis placed on making connections between theory and reality and connections between parts of the theory.

In putting the hardware for the lab together, the philosophy was to use simple hardware that represents systems common in industry, that involves many of the students' senses, and that minimizes the student effort in understanding the apparatus and in finding parameters for models of the systems. Therefore, we chose to construct a single electromechanical apparatus with a brushless servomotor and with encoders for measurement and feedback. We chose the components of the system to give a range of time constants and frequencies in the dynamics of system. Different parts of the dynamics can be observed visually, tactilely, audibly, and through high-speed data acquisition. Figures 1 through 3 demonstrate this hardware.

Figure 3 is a schematic representation of the motorlab system in a closed-loop position or velocity control configuration. There are two position sensors on the apparatus. The position of the motor inertia is measured using the motor encoder and the position of the load inertia is measured using the load encoder. This is done using hardware on the DSP motion control card. The velocities of the two inertias are measured using hardware on the motion control card that measures the time between pulses coming from the encoders. The motor amplifier has a control loop that measures and controls the electric current in the motor windings. This results in what is commonly known as a "torque controlled" motor, since the magnetic torque is approximately proportional to the current in the windings. The DSP motion control card is interfaced to the motor amplifier through a +/-10V analog signal from a digital to analog converter (DAC) on the card. By varying the magnitude of this voltage from the DAC the current in the motor is varied. This voltage, which is proportional to the controlled current, serves as a current command for the current control loop in the amplifier. An additional sensor, not shown below, is the current sensor in the amplifier. The DSP card also reads this sensor using an analog to digital converter

(ADC). Although the control loops on the DSP card do not use this signal, the software records it for analysis of the closed loop electrical dynamics.

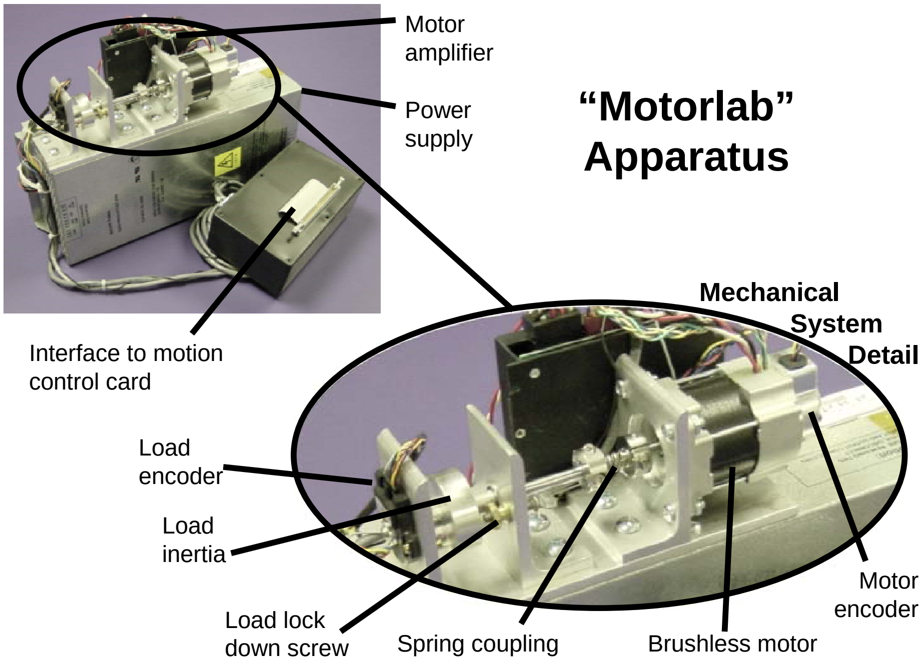
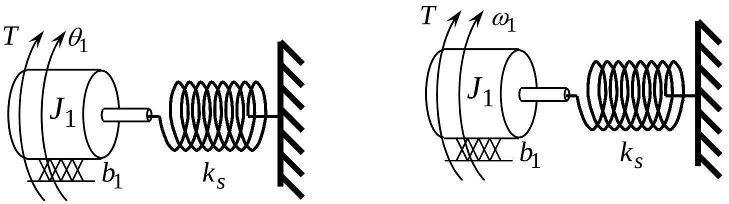


Figure 1: Motorlab Aparatus

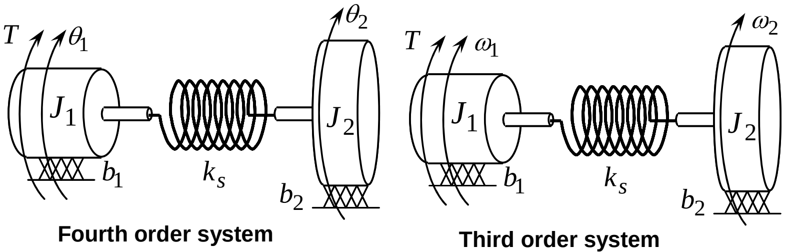
Second order system with a free integrator

First order system



Second order system

Second order system with a free differentiator



Fourth order system with a free integrator

Third order system

Figure 2: Motorlab Configurations

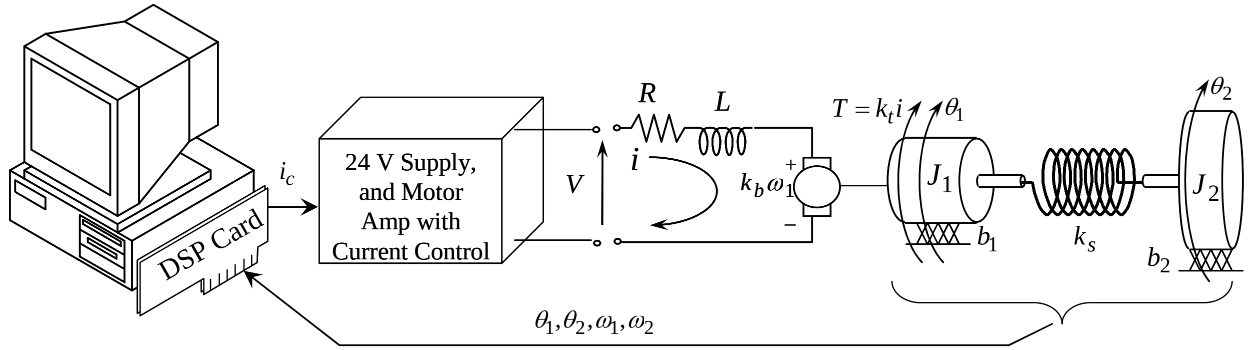


Figure 3: Schematic Depiction of Closed Loop Motorlab Systems

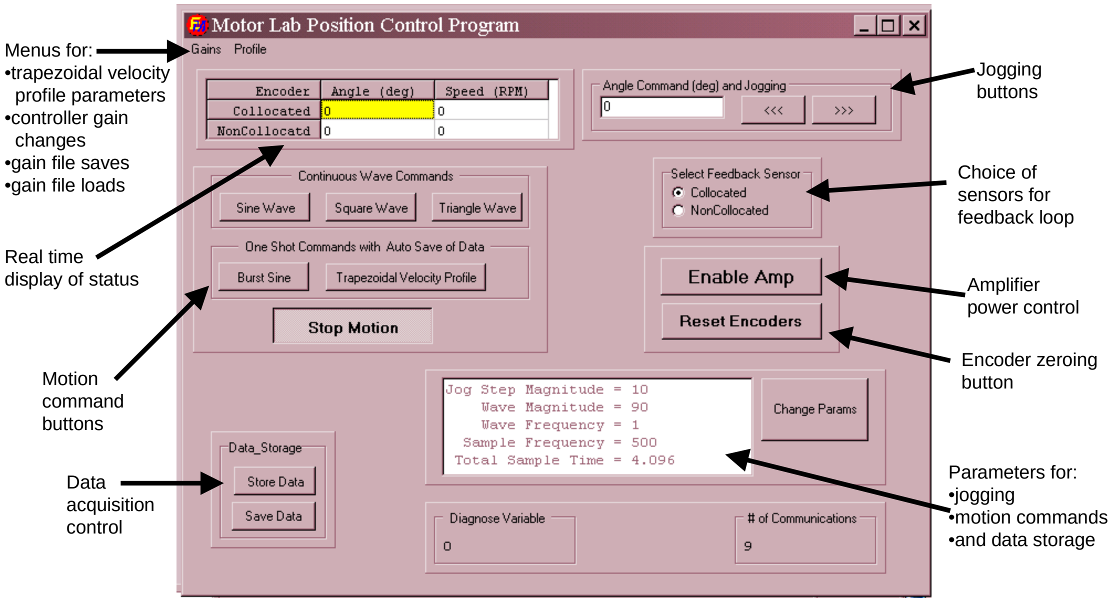
The experiments utilize several different configurations of the system. Either sensor, the motor or load encoder, can be used for the feedback of the control loop. The selection is made in the software interface. The motor encoder is known as a “collocated” sensor since it is co-located with the input to the mechanical system, the motor torque. A spring dynamically separates the load sensor from the input to the system. Therefore this sensor is known as a “non-collocated” sensor. In addition to varying which sensor is used, students change the mechanical system with the lock down screw and the spring coupling. In addition, students choose between velocity control, position control, and an open loop system by selecting the appropriate control program. Any of the following mechanical models may be realized using the motorlab hardware and software.

There are many, many machine axes, actuators, and motion systems driven by electromechanical servomotors. The nominal dynamics of these systems are very similar in most cases, involving inertia, friction, and flexible components in some cases. A simple motor and spring can capture these dynamic effects and still be easily related to more complicated industrial systems. As is commonly done in industry, a motor amplifier with a current control loop provides power to the motor. This does two things: it allows the early labs to focus on simple mechanical dynamics by making the electrical dynamics “fast” and it demonstrates a common technique in controls practice which is the closure of control loops at multiple levels in the system to improve performance.

Although choosing a single apparatus for most of the lab exercises may seem to give a narrow focus to the lab the benefits far out weigh the draw backs. The apparatus has many different aspects to keep the students interest throughout the semester, facilitates learning by reducing the amount of time in each lab explaining and understanding new hardware, and is an example of extremely common components found in industry. The mechanical dynamics of the system are configured differently by changing the coupling of the motor and by changing the controlled variable between position and velocity. Furthermore the electrical dynamics can also be studied and must be considered when attempting to get high performance from the system.

In putting the software together for the laboratory the philosophy was to make the software as easy as possible for the students to use while incorporating common control structures from industrial applications. We developed the software in house. This allowed us to develop software that incorporated industrial control structures and hardware while providing the ability to experiment. It is not possible to experiment significantly in the software available for industrial control applications. The software includes standalone programs to experiment and collect data using the motorlab hardware. It also includes MATLAB routines to import data and generate a standard set of plots. The students write MATLAB scripts to analyze the data, to perform theoretical analysis related to the laboratories, and to generate appropriate plots.

There are three different programs used to control the motorlab hardware: a position control program, a velocity control program, and an open loop program. Each program consists of a graphical user interface (GUI) that runs on the host PC and a low-level control program that runs on the digital signal processor (DSP) on the motion control card. The PC's processor and the DSP communicate over the PCI bus in the host computer. The two programs that implement closed loop control use a PID controller. In addition, the student has the option of including feedforward velocity and acceleration gains. The following figures show the GUIs.



Encoder	Angle (deg)	Speed (RPM)
Collocated	0	0
NonCollocatd	0	0

Angle Command (deg) and Jogging: 0

Select Feedback Sensor: ● Collocated ○ NonCollocated

```
Jog Step Magnitude = 10
    Wave Magnitude = 90
    Wave Frequency = 1
  Sample Frequency = 500
 Total Sample Time = 4.096
```

Diagnose Variable: 0

# of Communications: 9

Menus for:
- trapezoidal velocity profile parameters
- controller gain changes
- gain file saves
- gain file loads

Real time display of status

Motion command buttons

Data acquisition control

Jogging buttons

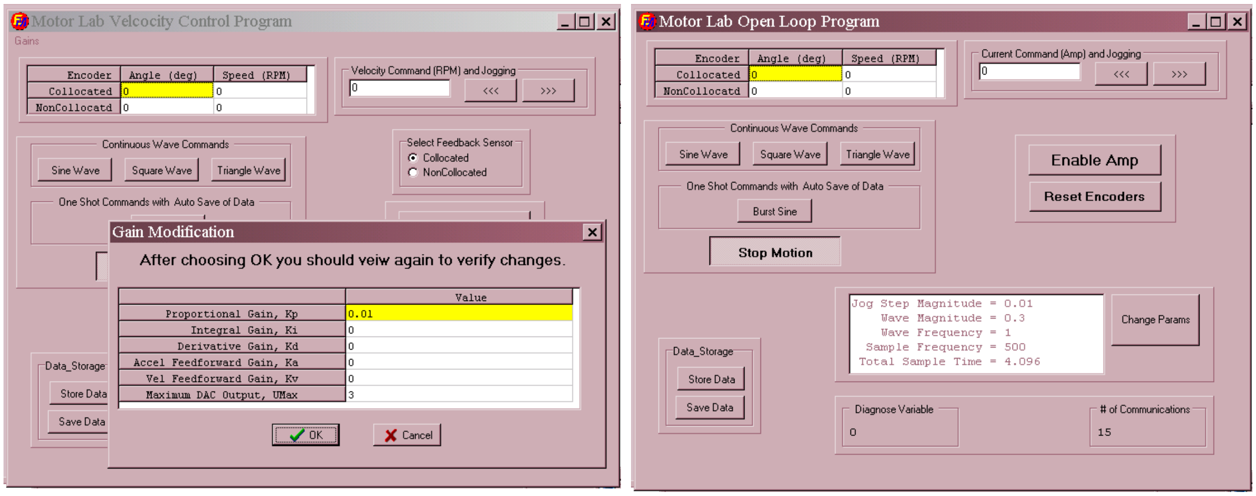
Choice of sensors for feedback loop

Amplifier power control

Encoder zeroing button

Parameters for:
- jogging
- motion commands
- and data storage

Figure 4: Position Control Host Computer Interface



Encoder	Angle (deg)	Speed (RPM)
Collocated	0	0
NonCollocatd	0	0

Velocity Command (RPM) and Jogging: 0

Select Feedback Sensor: ● Collocated ○ NonCollocated

After choosing OK you should veiw again to verify changes.

	Value
Proportional Gain, Kp	0.01
Integral Gain, Ki	0
Derivative Gain, Kd	0
Accel Feedforward Gain, Ka	0
Vel Feedforward Gain, Kv	0
Maximum DAC Output, UMax	3

Encoder	Angle (deg)	Speed (RPM)
Collocated	0	0
NonCollocatd	0	0

Current Command (Amp) and Jogging: 0

```
Jog Step Magnitude = 0.01
    Wave Magnitude = 0.3
    Wave Frequency = 1
  Sample Frequency = 500
 Total Sample Time = 4.096
```

Diagnose Variable: 0

# of Communications: 15

Figure 5: Velocity Control Interface Showing the Gain Change Dialog and Open Loop Control Interface

In the open loop program the feedback sensors (encoders) are not actually used for closed loop control. The DAC output from the motion control card to the motor amplifier is determined directly by the wave command buttons and the jog buttons. In position control the feedback sensors (encoders) are used to close the position control loop. The controller algorithm determines the DAC output from the motion control card to the motor amplifier, while wave command and jog buttons determine the position command. The velocity control program is similar to the position control program.

When the “Store Data” button is pressed in the host GUI the software stores data from the dynamic system in a circular buffer. Pressing either the “Save Data” button or the “Store Data” button again will stop data storage, leaving the last 2048 data samples in the buffer. If for example the sample rate is set to 500 Hz, then the last 2048/500=4.096 seconds of data will be saved in the buffer. The data is saved to a file by pressing the “Save Data” button. The exception to this sampling scheme occurs when one of the command buttons in the “One Shot Commands with Auto Save of Data” is pressed. In this case the command generation and the data storage execute until the buffer fills. Then the data is automatically stored to a data file named with the time and date from the computer clock. Eight pieces of data are stored at each time step (each sample period): time, the command (position, velocity, or motor current), the two angles, the two velocities, the motor current command, and the measured motor current.

Coalescing labs, homework, and lecture

In the course we struggle to keep the lecture, labs and homework in step with each other so that the students are experiencing the current topics in many different ways. This requires that the students work on assignments in a timely manner. It also requires a high level of coordination in the course and some flexibility in the laboratory assignments.

In most cases homework assignments are due at the next class period after they are assigned. There are usually two assignments per week. The assignments relate directly to topics covered recently. The philosophy of this is that it allows us to build on the concepts in laboratory and in the following class period. Many students are resistant to this rigid schedule early in the semester, making comments such as, “This isn’t the only class that I have.” However, with consistent explanation of the philosophy behind it, most accept it and begin to see its value. In nearly all cases a solution to the homework is made available to the students at the time the assignment is made. This enables us to ask difficult questions on the homework and to reuse good homework assignments from one semester to another. The students are told that they should attempt the homework without the solution, referring to it as needed. If the students turn in homework that appears to be a copy of the solution they are given a zero or a very low score. Although the homework is a very small percentage of the total grade, requires a significant amount time, and does not necessarily resemble the questions on exams, most students are diligent in doing it. Typically, a few students with low scores begin to do the homework more diligently after the first exam. Part of the success of this approach to the homework is that the philosophy behind it is clearly explained to the students. This philosophy is modeled on one way in which the author learns himself; to work out the details of a problem that I know the answer to using another's solution only when needed, making the solution my own. This also appeals to the student's responsibilities in taking ownership of their education, which they will respond to if given reasonable opportunities.

Since the topics in the labs, lectures, and homework assignments are closely related temporally, it is possible for the students to have not seen all the relevant topics in lecture and homework when they are working with it in lab. In fact, because there are multiple lab sections on different days some sections may have seen more of the material at the time of their lab. However, before the laboratory report is due the following week they have covered all the material in lecture and homework. This requires some flexibility in the approach for each individual laboratory. Students may treat them as an exploration or as a verification and substantiation of concepts.

As an example of how the lab, lecture and homework work together consider the concept of "low frequency gain." We use Figure 6 to explain the concepts in loop shaping design techniques. One of the goals in these techniques is to "shape" the magnitude of the open loop transfer function (OLTF) so that it has high gain (magnitude) at low frequency. This can be described as attempting to maximize the area under the OLTF magnitude before the crossover frequency, where it crosses the zero dB magnitude line. This is done by choosing the parameters of the controller wisely. Doing this will improve the control system's ability to track commands that change quickly and its ability to reject external disturbances acting on the system. Where the OLTF magnitude is large the closed loop transfer function (CLTF) magnitude is approximately one and the error is small, meaning the output will track the command.

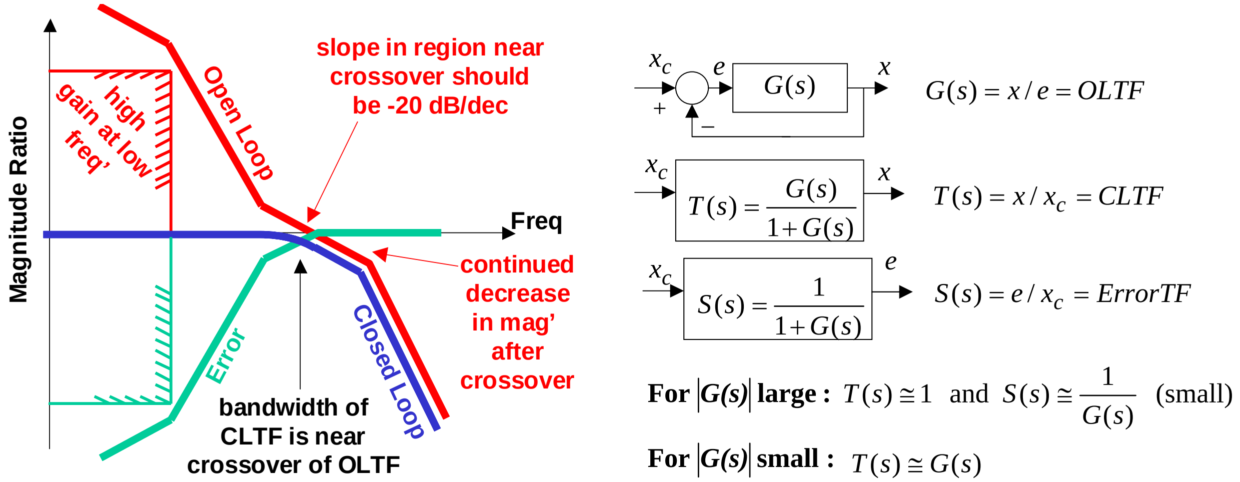


Figure 6: Figure used to describe "loop shaping" design techniques in class

In the lecture, the reasons for increasing the open loop gain are discussed and methods of getting high open loop gain are discussed and demonstrated through examples. The students are asked to put this into practice in homework exercises. That same week in the lab the students experiment with two different position controllers on the motorlab system. The two systems have approximately the same crossover frequency (and therefore bandwidth), but different open loop gains. They use the controllers to attempt to track high acceleration position commands like that shown in Figure 7. This command is generated using a trapezoidal velocity profile, which is commonly used for command shaping on multi-axis machine tools. We also ask to grab the shaft of the motor and to twist is sharply to generate a disturbance.

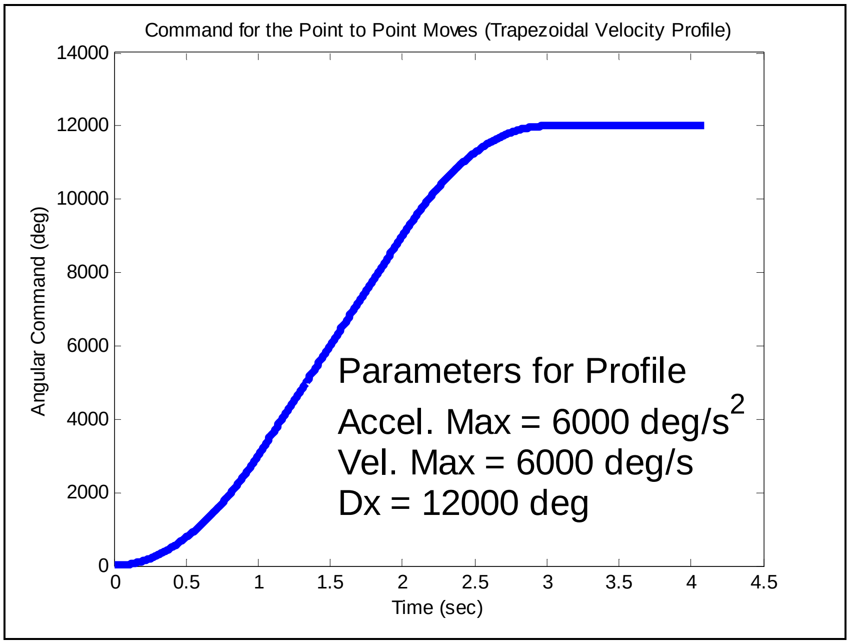


Figure 7: Position command generated with a trapezoidal velocity profile

In the lab the students find that the system with the higher open loop gain tracks the high acceleration commands much better and that it rejects the disturbances much better. They observe the disturbance rejection with tactile sensing in their fingers. They observe the tracking capabilities with plots. In the report the students discuss the implications of this in terms of the throughput capable of multi-axis machines with high gains versus those with low gains, both with the same accuracy constraints.

In these exercises the students experience the open loop gain concept in several different ways at nearly the same time, and they relate it to application. Furthermore arriving at the techniques to analyze and shape the gain has required significant mathematical background, which has been covered in the class, including dynamic modeling of engineering systems. The mathematical background includes writing differential equations that model a system, Laplace transforms, and in analysis using complex numbers and functions. They use all of these in application before leaving the course. Furthermore, the students are made aware of the power of transform methods. The loop shaping techniques are based on transfer functions obtained with the Laplace transform. These frequency domain descriptions of the systems allow them to apply a few simple concepts to obtain a good control system.

Reducing topical coverage but increasing expectations

It is the author's view that courses similar to the one discussed in this paper typically attempt to cover too much detail at the cost of not conveying the basic concepts of feedback control and of modeling and design with transfer functions. In designing the course discussed here, one objective was to reduce the number of specific topics while increasing the expectations for real understanding of the basic concepts of the course. To describe this an example will be used.

In a typical first course covering feedback control the root locus design technique is covered in detail and frequency response techniques are covered quickly, if at all. This is true despite the fact that the majority of the industrial practitioners designing simple control systems for single input, single output systems rely on frequency response techniques. One of the reasons for this is topical bloat in the related textbooks and the fact that frequency response techniques are covered after root locus techniques. To cover the root locus as a quantitative design technique where controller gains are actually calculated from a model requires a great deal of mathematical background. To deal with this issue we decided to cover root locus simply as a "qualitative" design technique using only the basic rules that allow the students to sketch and modify the basic shape of the root locus for a system. This allows the course to skip specific topics that take several weeks of the semester to cover, while making time for topics such as the effects of large (high frequency) poles and zeros on the shape of the root locus near the origin of the s-plane (at low frequency). This is an important topic, covered by none of the common texts known to the author. It is important because any practical system model we will ignore an infinite number of poles and zeros at higher frequencies than those of the nominal model of the system, or will account for them in with rough approximations only. These higher frequency dynamics will almost always limit the performance of the closed loop control system. Furthermore, covering this topic builds important connections to frequency response techniques covered later. The students are expected to make these connections between the two techniques and between the root locus technique and its practical use for real systems with practical models.

Finding, reiterating, and building on key concepts throughout the course

Again, it is the author's view that courses similar to the one discussed in this paper often present many of the topics in course as disjoint subjects with little connection between them. This results in compartmentalized knowledge that is of little use to the students, and forgotten quickly. While the students can work simple problems with such knowledge, they do not have a true understanding of the subject of the course and in many cases finish the course more confused than when they started. One method employed in dealing with this problem in the course discussed here is to use a few key concepts throughout the semester to tie subjects together and to build on. An example of these concepts is the "higher frequency" dynamics discussed in the previous section. The following is an example of how this concept is used throughout the semester.

Some of the higher frequency dynamics of the Motorlab system are the electrical dynamics depicted schematically in Figure 3. The system represented by this part of the schematic is the motor amplifier and the electrical elements of the motor, with a closed loop current controller. In the first lab of the semester, the students are introduced to this closed loop system. We tell them for the time being we will consider it to be "fast" compared to the dynamics of the mechanical system. Through a class discussion they arrive at the result that perhaps a good transfer function model of this is a one, meaning whatever current is commanded is instantaneously realized in the motor windings. Shortly after this, in the modeling portion of the class, they complete homework and a lab where they model and experiment with this part of the motorlab. They discover that in fact the poles and zeros of this closed loop system are much larger than those of the nominal mechanical dynamics. In the following lab, focusing on dominant poles and zeros, they discover that the larger poles and zeros can be ignored in the overall response of the system.

Following this in the root locus portion of the class they generate a root locus with and without these higher frequency dynamics. They discover/verify that the shape of both are the same near the origin of the imaginary plane (at low frequency), but that the inclusion of the electrical dynamics will cause the model to be unstable a high control gains when the poles of the closed loop system move farther out from the origin. In the frequency response portion of the course they complete homework and lab where they find that using a simple/realistic position controller that the bandwidth of the current control loop is a limitation on the bandwidth of the position control system. In the final lab of the semester they are asked to pretend as if they do not know the details of these higher frequency dynamics, but rather to find their limiting effects through a tuning process for a velocity control loop. Throughout all of this they are continuously asked to relate what they are finding back to what they have seen before in the previous parts of the course.

We also use the example of the motorlab electrical dynamics to illustrate another key concept related to the concept of higher frequency dynamics. We use it to illustrate the concept of building multiple control loops in the design of a system.

The use of these "key concepts" allows us to tie all parts of the course together from the mathematics of differential equations, to modeling using the first principles of physics and dynamics, to higher-level discussions of the transient response of a complicated system, to control system design and tuning, and to good engineering practice.

Conclusion

The course described in this paper is a course that is taught earlier in the curriculum than most similar courses in other curricula. It was designed with three major themes in mind: 1) often, less is more in the context of the topical coverage and retention and understanding, 2) application of material and active learning are important motivating factors for the students, and 3) moving engineering application to earlier in the curriculum engages the students in the curriculum. By eliminating some typical prerequisites and it gets to engineering application earlier in the curriculum. This allows the course to integrate the learning of advanced mathematics, engineering science, and engineering application into a single course, which the author contends increases the actual amount of material learned and retained. This does however require the reduction of specific topical coverage in any one of the single areas. In the specific situation within the Mechanical and Nuclear Engineering Department at Kansas State University, this has resulted in a course that is accepted much better by the students than its predecessor(s) with increased learning and retention by the students.

Biographical Information

DALE E. SCHINSTOCK is a faculty member in the Mechanical and Nuclear Engineering Department at Kansas State University. He received his Ph.D. from the University of Kansas in 1994. From 1994 to 1998 and from 1998 to 2001 he was faculty in the Mechanical Engineering Departments at The University of Alabama and The University of Tulsa, respectively.