

PROMOTING AND ASSESSING INTUITIVE UNDERSTANDING IN A JUNIOR-LEVEL MODELING COURSE

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ABSTRACT

Many faculty have observed that even the best engineering students have difficulty taking a complicated real-life device and developing a tractable mathematical model of its operation for the purposes of simulation or control design. We feel that the major obstacles to this desired outcome stem from three deficiencies.

1. Difficulty in using appropriate simplifying assumptions to render a tractable mathematical model of a complex device.
2. A lack of experience in designing experiments to measure physical parameters of a device and a lack of intuitive understanding of the appropriate ranges of these parameters.
3. Failure to use electronic resources such as databases and internet to discover how more complicated devices, not discussed in lecture, operate.

In fact these issues are explicitly addressed in ABET's *Criteria for Accrediting Engineering Programs*.

While traditional textbook and exam problems do a fine job conveying the procedural and mathematical concepts of modeling physical systems, it is much more difficult to give students an understanding of the artful aspects of the modeling process outlined above. In this paper we describe a series of laboratory and homework exercises designed to help students hone these skills, discuss how to assess their performance on the exercises and share the results of student opinion surveys.

1 Introduction

In the Systems Engineering Department at the United States Naval Academy all students are required to take a junior level course on mathematical modeling. During their senior year all students in the department form teams of two or three to design and build a device. Many of these projects contain some type of basic automatic control system. Most projects are inspired by students' upper level electives. Ideally students would develop a detailed mathematical model of their system and use this model for simulation, performance prediction and control system design. Since it is a device of their choosing, it is unlikely that they have had prior classroom exposure to all the device's components.

Despite the fact that students have learned to model basic systems and develop transfer functions and state space models in their Junior year, it is rare that a group applies these principles to their senior

project without considerable faculty guidance. An *ad hoc* committee was formed to investigate the source of this disconnect and three major obstacles to this desired outcome were identified.

1. Difficulty in using appropriate simplifying assumptions to render a tractable mathematical model of a complex device.
2. A lack of experience in designing experiments to measure physical parameters of a device and a lack of intuitive understanding of the appropriate ranges of these parameters.
3. Failure to use electronic resources such as databases and internet to discover how more complicated devices, not discussed in lecture, operate.

ABET's *Criteria for Accrediting Engineering Programs* acknowledges that these are critical skills for engineering students. They identify the following criteria:

Criteria e: an ability to identify, formulate, and solve engineering problems.

Criteria b: ability to design and conduct experiments, as well as to analyze and interpret data.

Criteria j: recognition of the need for, and an ability to engage in life-long learning.

Despite the universally accepted importance of these skills, deficiencies appear to be widespread. Indeed at the 2004 ASEE conference the plenary speaker, Woody Flowers, echoed this sentiment at a national level. He presented data showing that while the technical abilities of today's engineering students are as good or better than their cohorts from 30 years ago, their ability to think intuitively about engineering systems has declined significantly. He cited poor performance by MIT students at mentally "guestimating" engineering quantities, determining how devices work by disassembly, and debugging hardware and software setups, for example. Note that these were students who are in the top 1% of college freshman with respect to admissions metrics such as high school GPA and SAT scores.

Our explanation of this phenomena is that while traditional textbook and exam problems do a fine job conveying the procedural and mathematical concepts of modeling physical systems, it is much more difficult to give students an understanding of the artful aspects of the modeling process outlined above. After giving a more detailed background of the course in Section 2, we describe a series of laboratory and homework exercises designed to help students hone these skills, and discuss the difficult issues of how to assess their performance on the exercises. In Section 3 we discuss the use of assumptions, Section 4 addresses parameter measurement exercises, and Section 5 gives examples of assignments used to promote life long learning. Many of the exercises address more than one of the issues discussed above, however they were categorized into the primary skill they address. In Section 6 we summarize and share the results of student opinion surveys.

2 Course Overview and Learning Objectives

The Systems Engineering major at the United States Naval Academy's has at its core a feedback control system focus, with opportunities for students to take upper level courses in several application areas including robotics and embedded control systems. ES301, "Dynamic Systems Modeling and Simulation," is required for all students in the major and is typically taken during the junior year. The course is organized as two one-hour lectures and one two-hour laboratory exercise per week. The objectives of the course are to have students become proficient in constructing mathematical models, such as transfer functions and state space models, of various physical systems, such as mechanical, electrical and hydraulic systems. In addition topics such as numerical

integration, system identification, and the use of MATLAB and SIMULINK tools within the modeling context are covered. Prerequisite topics include: differential equations, basic matrix algebra, LaPlace transforms and prior exposure to college level physics.

Despite the fact that students have learned to model basic systems and develop transfer function and state space models in ES301, it is rare that a group applies these principles to their senior project without considerable faculty guidance. In an effort to address this deficiency we have three additional Learning Objectives:

1. Assumptions: Students should be able to go from a physical device to a schematic diagram that captures the relevant qualitative behavior of the original system, list their assumptions and describe the impact of each of them.
2. Estimation and measurement: Students should have some experience measuring physical parameters, directly and indirectly, and have an intuitive feeling for appropriate ranges of numerical parameters.
3. Life Long Learning: Students should develop the habit of using electronic resources such as databases and internet to discover how more complicated devices, not discussed in class, operate.

3 Use of simplifying assumptions

Assumptions are required to simplify the operation of complex devices before the standard modeling techniques covered in lecture can be applied. This is one of the most difficult skills to teach. Assignments addressing this are covered in this section.

3.1 Homework problems

In the course, we cover various modeling domains including mechanical translational and rotational systems, electrical systems, fluid systems, thermal systems and mixed systems. As each type of system is covered in lecture, a homework exercise is assigned. Most of the assignment consists of schematics of systems constructed out of basic components (e.g. masses, springs and dampers or resistors, capacitors and inductors) and asks the student to develop a transfer function, state space model or simulation. However, the final question in each assignment asks students to develop such a schematic on their own. An example, in the case of mechanical translational systems, follows.

Think of an everyday device, not discussed in detail during lecture, which is a Mechanical Translational system.

- a. *Make a sketch of the system.*
- b. *Write a sentence describing what it does.*
- c. *Draw a schematic representation of the system's model using masses, springs or dampers.*
- d. *Add a coordinate system and label the nodes.*
- e. *List any assumptions you made in constructing the model (e.g., you may have assumed something was massless, modeled a flexible structure with springs, friction with dampers, etc.)*

The question is graded according to three criteria:

- Creativity in model selection: Often students will select devices containing obvious springs, damper and masses, such as a car shock, which were mentioned in passing during class. Other students will go to great lengths to select less obvious or more complex examples such as mechanical pencils, aircraft carrier landing arrest systems, etc.

- Validity of schematic: Does the student’s simplified representation still reproduce the basic operation of the device? Students are encouraged to ask themselves this question. In the example of the aircraft carrier landing arrest system some students put the spring and damper icons in parallel instead of series. A parallel placement would cause the plane to spring back to its initial touch down position.
- Care in identifying assumptions: Most assumptions are implicitly encoded in their schematic, so their validity is considered above. However, asking students to explicitly list assumption serves the dual role of forcing them to critically examine their model and providing them with an opportunity to practice their technical communication skills.

It was our observation that student submissions from the beginning of the semester are much more naïve, showing the influence of the source information and the lack of criticism on the part of the students. By the end of the semester students tend to produce stronger answers in all three categories.

3.2 Laboratory experiences

In a sequence of three labs students were asked to model and develop a simulation of the system shown in Figure 1, consisting of two Quanser Inc. devices – a flexible linkage (Rotflex Module), attached to a DC motor (SRV02). The system represents a simplified model of a robotic arm.



Figure 1: Flexible Joint and DC motor.

The first week’s assignment focuses solely on the flexible link attachment (Rotflex Module). Students are asked to:

- Draw a schematic of the system. Be sure to indicate any assumptions or approximations.*
- Create a linear mathematical model of the system (i.e., a set of differential equations).*

Step (a) required significant instructor assistance since there are several ways to model the flexible joint system that are not obvious. Many students are confused by the fact that, while the system is obviously strictly rotational, the two springs at the base are clearly translational springs. Upon inspection it is apparent that the springs do not behave in a linear manner especially at the extreme

ends of their range of travel. Also, there is no obvious “damper”. Some students do not realize that air resistance, friction at the bearing and connection points and molecular friction in the springs all contribute to overall damping but their effects can be lumped into a single damper.

The instructors recommended that the students model the two linear springs at the base of the link as a single rotational spring. It was also recommended that the students model all of the frictional effects as a single viscous rotational damper in order to preserve the linearity of the model.

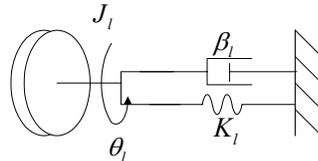


Figure 2: A schematic model of the system in Figure 1.

Once these assumptions are understood, Step (b) proved to be an easy task for the midshipmen due to the correlation with the classroom lecture. The final equation of motion for the rigid link flexible joint system is given by:

$$J_l \ddot{\theta}_l = -\beta_l \dot{\theta}_l - K_l \theta_l + \tau_l \quad (0.1)$$

where τ_l represents any applied torque to the link, J_l is the rotational moment of inertia, β_l is the effective linear damping coefficient, and K_l is the lumped rotational spring constant.

4 Experiment design and parameter estimation

A mathematical model is not useful, for simulation or analysis, without numerical values of its parameters. This section addresses parameter “guestimation”, as well as direct and indirect parameter measurement.

4.1 Homework Problems

It is important that once students experimentally measure parameter values, they are able to determine if their results are reasonable. Making such a determination requires that one knows the expected range of answers. However, most students have had little or no prior practical exposure to parameters such as a damping ratio or an inductance, and lack the ability to “guestimate” the correct answers. Practice is required to hone these skills. The following assignment provides such an opportunity.

For each parameter below select a reasonable value, justify your answer:

Spring constant for mountain bike shock:

- a. 6 N/m
- b. 660 N/m
- c. 6600 N/m

Hint: What is your weight in Newtons? How much might a bike deflect if you sat on it?

Inertia of ship propeller.

- a. $2 \text{ Kg}\cdot\text{m}^2$
- b. $200 \text{ Kg}\cdot\text{m}^2$
- c. $20000 \text{ Kg}\cdot\text{m}^2$

Hint: Look up the formula for the moment of inertia of a disk (approx). Assume the radius is 1-2 meters.

Torque required to turn a door knob.

- a. $0.1 \text{ N}\cdot\text{M}$
- b. $10 \text{ N}\cdot\text{M}$
- c. $100 \text{ N}\cdot\text{M}$

Hint: Think about hanging a 1 Kg weight on a rod of length _____. Would that be enough torque to open a door?

Students are evaluated both on the accuracy of their answers and the plausibility of their reasoning.

4.2 Laboratory experiences

We design laboratory exercises that give students practice measuring parameters in both direct and indirect ways. Consider again, the assignment described in Section 3.2. Once students develop a schematic and mathematical model of the flexible link system, as shown in Figure 2, the next step asks:

- c. *Determine what physical parameters are needed for the model. Devise a set of experiments to determine their numerical values.*

This is left as an open ended exercise, where step-by-step instructions are not provided.

Most students use a ruler and scale to determine the dimensions and weight of the link, then compute the moment of inertia, J_l , according to commonly tabulated formulas. Students also devise an experiment to compute the spring constant, K_l . Many suggest disassembling and removing the springs and hang weights from them. Disassemble is strongly discouraged for fear of damaged equipment. Other students determine K_l , by measuring the joint's angular deflection under its own weight when laid on its side, as in Figure 3.

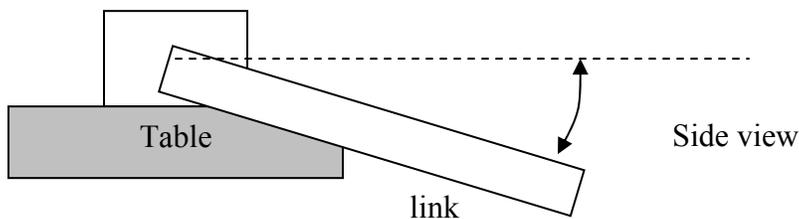


Figure 3: Typical student experiment to determine the rotational spring constant K_l .

Here students must also analyze assumptions. Many students chose to ignore the holes drilled in the bar when calculating its inertia, or to employ a “slender rod” assumption. The spring is not truly linear but because the range of deflection during typical operation is limited the assumption is valid.

In other labs, indirect measurement of numerical parameters is suggested. For example, in a follow up assignment, students are asked to create a simulation of the DC motor (SRVO2) shown in Figure 1. The motor is assumed to have negligible inductance and viscous friction. The transfer function from applied voltage to shaft rate is $\frac{\Omega(s)}{E(s)} = \frac{K_{TB} / RJ}{s + K_{TB}^2 / RJ}$, where K_{TB} is the numerically equal back E.M.F. constant and torque constant, R is armature resistance, and J is armature's moment of inertia. Students must determine each of these parameters.

At first glance the measuring R with an Ohm meter seems straightforward. However, the students find that the measured resistance will vary somewhat depending upon how the brushes lay on the commutator after each time that the motor shaft has been turned. This is an interesting discussion point. The remaining two parameters must be inferred from an actual experimental response, seen in Figure 4, since the motor cannot be disassembled.

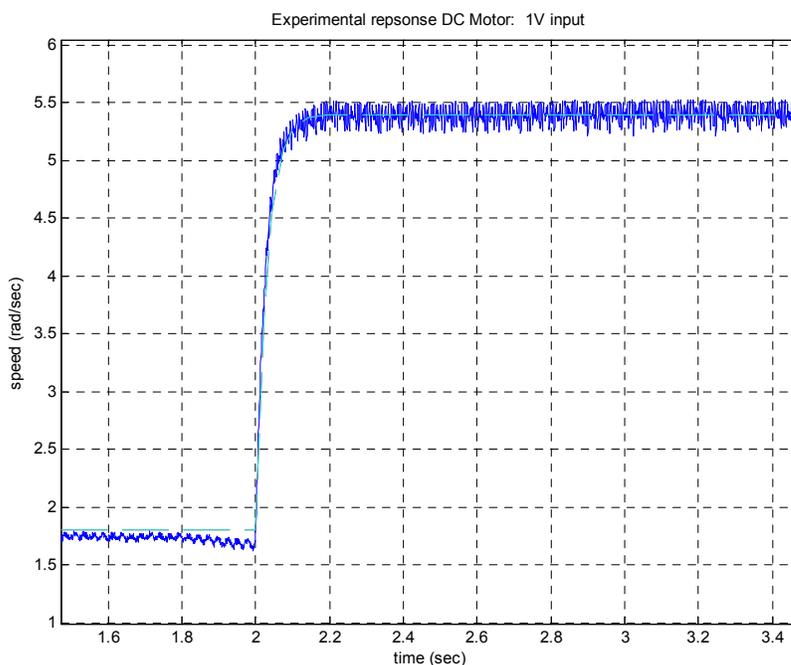


Figure 4: Experimental response (angular velocity) of the DC motor after applying a 0.5V to 1V step input.

DC gain is $1/K_{TB}$, so K_{TB} follows directly from the measurement of applied voltage and steady state shaft rate. However, because the steady state shaft rate is determined from tachometer voltage the trace of shaft rate as a function of time is not smooth (see Figure 4), due to the tachometer brushes and commutator. An additional complication is that, while a single input-output measurement pair should suffice, K_{TB} tends to vary slightly based on the applied voltage. In light of this non-ideal behavior, students must determine which measured value to actually use.

Once R and K_{TB} are known, J can be determined based on the rise time. The 10% to 90% rise time, T_r , of this first order model is 2.2 time constants. Systems theory predicts $T_r = \frac{2.2RJ}{K_{TB}^2}$. In principle T_r is readily measurable from a step response, but due to static friction the rise time is quite different if the initial shaft rate is nonzero, as compared with a motor initially at rest.

The students are surprised to see that there is much more than meets the eye to finding the parameters for such a simple electro-mechanical system. The discussion of the variations from one trial to another and the rough step response traces lead to the topic of least squares parameter estimation, a topic of the follow-on course. Finally the students find that the model based upon careful measurement procedures, does not accurately predict experimental behavior. What has been left out is constant friction, a non-linear behavior that cannot be modeled by the linear Laplace transform technique. This is a further motivation to study and apply simulation diagrams that can incorporate non-linear elements.

5 Use of electronic resources for lifelong learning

In the last ten years, the Internet has exploded into a massive sea of knowledge. While having so much information readily available is an invaluable resource, the difficulty in sifting through the many resources available sometimes deters individuals from using the World Wide Web fully.

In our course, we make a conscious effort to use electronic resources in order to promote lifelong learning. In the classroom, Web links are displayed and used as part of lectures. Students are made aware of and shown resources that are provided online. While it is useful to present web resources during lecture, we also realize the importance of promoting the use of electronic resources outside of the classroom in homework assignments and laboratory exercises.

5.1 Homework Problems

Often throughout the semester, we simplify the system being discussed in order to mathematically model it using the techniques taught during the semester. Unfortunately, although this process allows students to learn how to mathematically model the system, sometimes the real engineering system or the overall picture gets lost. In order to keep the students connected with real systems and instill the fact that these types of systems are present all around them, we assign problems that force the students to look up engineering systems via the web.

For example, when introducing the topic of gears, the following assignment tasks students with extending this basic knowledge to other types of gears.

The most basic type of gear that we have discussed in class is called a spur gear. Go to www.howstuffworks.com/gear.htm and answer the following questions.

- a. *How are helical gears different from basic spur gears?*
- b. *What is the advantage of helical gears?*
- c. *What is a common application of the helical gear?*
- d. *What are bevel gears?*
- e. *What are they used to accomplish?*

- f. *What are worm gears used for?*
- g. *Describe and explain one unique property of a worm gear.*

Unfortunately due to time constraints, we do not have the opportunity to explore many different examples of a specified type of system. This assignment introduces different and complicated engineering systems, which we may only get a chance to mention during the lecture. Thus, these types of homework problems can have the added benefit of allowing us to go into more detail of an engineering system as well as encouraging the use of electronic resources. Typical student responses to these questions were not as simple as expected. Many students went into great detail regarding the applications of the gears. This type of response indicates that this method of assigning homework problems is extremely promising in terms of promoting continuous learning.

While specific web pages or suggestions to use the internet can be provided in homework problems, problems can also be designed to promote the use of electronic resources without directly mentioning it. Several of the assignments discussed earlier fall into this category. For example, the homework asking students to estimate parameters described in Section 4.1 supports the use of electronic aides. For example, in one of our homework assignments, we ask, “What is the inertia of a ship propeller?” Most students looked up the formula for the inertia of a disk as well as the mass of a propeller that size on-line. In the series of assignments introduced in Section 3.1 requiring students to model everyday systems, most of the examples students cited were researched on-line.

5.2 Laboratory experiences

We have designed a specific laboratory assignment that makes it necessary for all students to become familiar with scientific databases.

Log onto IEEEExplorer. Search for a conference paper that models an engineering system using state space equations or a transfer function. Write a short report and 5 minute presentation which addresses criteria (a)-(g) below. If you do not feel that you can answer questions (a)-(g), then reread or select a new paper. Include:

- a. *A short description of the system. Include a diagram if needed.*
- b. *The uses for the model*
- c. *The mathematical model (write out the transfer function or state space model) and be able to explain what each of the variables are.*
- d. *A list of the inputs, outputs, states (if any), and disturbances (if any) for the model.*
- e. *Any assumptions used to develop the model. Feel free to include a critique of the paper.*
- f. *Reference of where you found the model*
- g. *A copy of the paper that contain your model attached as an enclosure*

During the scheduled laboratory time, students become familiar with IEEEExplore and its search engine. Instructors must approve each paper selected. The goal is to have students select a which is comprehensible, given their background. Yet at the same, students are encouraged to select a paper that describes an application not discussed in class, enabling them to learn about a new device.

Students are graded on three critical factors:

- **Communication:** Overall quality of report and presentation.
- **Paper Selection:** Demonstrating an understanding of the material, while selecting sufficiently challenging subject matter.

- **Critical Thinking:** Ability to identify the critical assumptions and limitations of the model's applicability.

Students unearthed a large variety of application contexts in their search. One of the most important parts of this kind of assignment is that it not only brings together many engineering concepts, but it also truly promotes lifelong learning by pointing students to available resources. This was readily observed through the enthusiasm displayed by the students when they were presenting the paper they chose to the rest of their classmates.

6 Survey and conclusion

In this section we discuss the result of student opinion surveys and discuss plans for future changes.

6.1 Survey results

Anonymous student evaluation surveys were administered to 80 students.

	<i>Question</i>	<i>Mean (out of 5)</i>	<i>Std. Dev.</i>
Q1	Do you think the homework questions which asked you to give an example of a system, helped you to connect the lectures to real devices?	3.82	0.93
Q2	Do you think homework problems which asked you to estimate a parameter value helped you to get a better physical understanding of the parameters discussed in lecture?	3.77	1.09
Q3	In lab, do you think working with physical systems, taking measurements and making simulations reinforced or expanded you understanding of the lecture material?	4.00	0.75
Q4	Do you think the final research project reinforced or expanded your understanding of the lecture material?	3.09	1.40
Q5	How likely are you to attempt to make a transfer function, state space model or simulation for your I/C project next year?	4.34	0.89
Q6	One of our goals as ES301 instructors is to give students a feel for how to go about modeling real systems. Overall, how successful were we?	4.18	0.75

Table 1: Results of anonymous student opinion survey. N = 80.

Overall, students were pleased with the attempts to connect the course to real life systems (Q6, Mean: 4.18/5). One students commented, “This course taught me to think like an engineer – to use a combination of know-how and mathematics to figure out what is important in predicting how systems work.” Q1 and Q2 had somewhat lower satisfaction scores but were overall positively received.

The laboratories were also relatively well received (Q3, Mean 4.00/5). An interesting observation in students' comments was a simultaneous desire to work with “real systems”, balanced by a tendency to rate hardware oriented labs lower because they “were difficult” or “the simulation failed to match the experiment”, occasionally reinforcing the notion that simulation was a waste of time. Clearly this is a delicate balance that instructors must strike.

Perhaps most importantly students indicated that they were highly likely to use mathematical modeling techniques on their senior projects (Q5, Mean: 4.34/5).

One interesting and constructive finding was related to the library research project. Of the questions on the survey, the mean student's satisfaction was lowest (Q4, Mean 3.09). However, student opinions seemed to vary widely on this, ranging from "this project gave me a chance to learn about a new device and let me see how the concepts from class applied to real world systems" to "this project was a waste of time". This observation is numerically supported by the large standard deviation, 1.4, in responses. Apparently student satisfaction seemed to be most determined by a student's choice of article. Students who rated the project poorly indicated that the level of the article they chose was over their heads. Students who had an easy time understanding the article rated the experience worthwhile.

6.2 Conclusions

It was observed that students are not very likely to apply concepts learned in the junior-level modeling class to their senior design projects. It was determined that the deficiency does not lie in the students understanding of the mathematical and procedural components of modeling but rather from a lack of experience with the more artful aspects. We identified three skills students required to improve in this area: use of assumptions, experimental parameter measurement and lifelong learning. A variety of homework and laboratory exercises were introduced which addressed these issues. Most of the assignments took the form of open ended questions. It is important to remember that these assignments were employed in addition to – not in *lieu* of – traditional analytical assignments. By fostering strong fundamental knowledge and fun applications we hope to give students an opportunity to become comfortable with the modeling process, rather than just solving specific close ended problems.

Never-the-less, these techniques alone will not guarantee that our objective – increased use of modeling techniques in senior projects – will be achieved. The best method of teaching is *via* example. To that end, the future goal for the instructors is to develop a comprehensive final modeling project, based on actual student design projects. Over the next few years select projects will be culled from the each year's design projects. They will be selected largely on the basis of being tractable, having parameter values that are easy to estimate or compute, and, yet, represent system not previously discussed in lecture. Students will be asked to determine the use of their model (e.g. control system design, performance prediction, component selection, etc.), develop detailed model, identify any assumptions and limitations, estimate parameters, and construct a simulation. The project will require them to use the skills discussed throughout this paper in addition to more traditional technical skills. The goal is ambitious but with proper project selection it is attainable. Once students complete this exercise in their junior year under close guidance, we feel they will be much more likely to repeat it in their senior year.