Abstract – Experiences are described in developing and using class-tested vignettes for streamlined learning in a senior control systems course. This new approach features an appeal to the students’ natural sense of curiosity on what might be consequences when changes they suggest are made in the design of a specific feedback system as well as significant reductions in computation required to test their suggestions. Four vignettes being used in the course are discussed with various levels of details in this paper, and brief remarks are made about two others. Surveys of students in a recent controls class indicated that the streamlined learning approach was received positively. These same students demonstrated improvements over previous students on the multidisciplinary team course project based on a team-selected controls application.

Index Terms – Learning process, Course development, Feedback principles.

INTRODUCTION

Basic feedback control system concepts continue to be taught today in much the same way they were presented several decades ago. While major concepts in systems modeling and representation, systems analysis, and controller design remain unchanged for the most part, what is amazing is that the associated techniques to promote student learning of these concepts have tended to remain the same, especially inside the classroom. Outside the classroom, students perform Matlab simulations to verify analysis and design results but these exercises are often not fully integrated with classroom experiences. In contrast, students today are eager to know immediately the consequences on system behavior from changes they suggest in the design of a specific feedback system. Such student interactions can be encouraged by using automated graphics and simulation tools directly in the classroom to show the effect of design changes.

Critics might argue that these presentations could be geared toward “dumbing down” concepts or (worse) only providing entertainment for the students rather than educating them. It is important not only to avoid such pitfalls in actuality by providing enhanced learning but also to guard as well against even the appearance. Recall that the over-riding premise is that learning can be enhanced further with modern laboratory projects and tests or examinations form strong, integrated, learning experiences.

Current courses on control systems are outdated primarily because they are based on textbooks that present a few simulation curves but focus strongly on hand-calculation procedures and possibly the use of programmable calculators [1-4]. Control algorithms from three and four decades ago continue to be perpetuated in present textbooks without considering fresh procedures now easily developed by using emerging educational technologies [5-12]. The main improvement in control system textbooks in the past two decades have been incorporating descriptions of many new control applications and providing supporting websites. Learning can be enhanced further with modern laboratory experiments [13-18]. Hopefully, new textbooks will embrace the learning improvements described in this paper.

CRITERIA FOR DEVELOPING VIGNETTES

Criteria used for deciding on specific topics and contents of associated vignettes were determined first. In their order of importance, these criteria are listed below.

1. Each vignette must convey a major feedback system concept that can be grouped under one of a few main categories defining the field of control systems.
2. Vignettes must avoid harsh computational formulas and chart-dependent techniques as much as possible, relying on simulations and automated graphics to present attractive and informative results.
3. Vignettes must allow the student to vary parameters and/or conditions to show the relative importance of these settings and the sensitivity of the system design.
4. While focusing on some limited aspect of the system, vignettes must also show the relationship to both time response and frequency response specifications.
5. Some vignettes may feature digital (or discrete-time) control procedures and others the consequences of random disturbances and/or nonlinear effects.
6. Vignettes must provide details on associated Matlab and Simulink programs for use by students in outside assignments on homework and the course team-driven computer project.

VIGNETTES FOR STREAMLINED LEARNING

Vignettes describing key control techniques were developed for senior students in a basic control systems course for electrical and computer engineering majors. Shown in Table 1, these vignettes were arbitrarily grouped as an analysis technique, a closed-loop property, stability, and controller design.
This vignette shows how changing rate feedback for second-order systems. The vignette provides a result applicable as well for tachometer or %OS with errors of only a few percent in both cases. This yields approximate curves of %OS versus formulas described above. Quadratic functions were fitted to approximate formula based on curve fitting to the exact Such harsh calculations can be avoided by using an term from the numerator.

<table>
<thead>
<tr>
<th>No.</th>
<th>Vignette Topic</th>
<th>Group/Category</th>
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<tbody>
<tr>
<td>1</td>
<td>System representation</td>
<td>Analysis technique</td>
</tr>
<tr>
<td>2</td>
<td>Per cent overshoot for time response</td>
<td>Analysis technique</td>
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<tr>
<td>3</td>
<td>Digital control: varying sample size</td>
<td>Analysis technique</td>
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<tr>
<td>4</td>
<td>System sensitivity</td>
<td>Closed-loop property</td>
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<tr>
<td>5</td>
<td>Steady-state errors</td>
<td>Closed-loop property</td>
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<tr>
<td>6</td>
<td>Effects of random disturbances</td>
<td>Closed-loop property</td>
</tr>
<tr>
<td>7</td>
<td>Effects of adding controller poles</td>
<td>Stability</td>
</tr>
<tr>
<td>8</td>
<td>Effects of adding controller zeros</td>
<td>Stability</td>
</tr>
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<td>9</td>
<td>Root locus</td>
<td>Stability</td>
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<td>Controller design</td>
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<td>11</td>
<td>Lag compensation</td>
<td>Controller design</td>
</tr>
<tr>
<td>12</td>
<td>PID control</td>
<td>Controller design</td>
</tr>
</tbody>
</table>

Table 1: Vignettes Developed for Control Systems course

Descriptions of Selected Vignettes

As illustrations, Vignettes 2, 3, 4, and 12 are described with various levels of detail in this section, and brief remarks are made about Vignettes 7 and 8. Student surveys focused on Vignettes 2, 3, 4, 7, and 8 are given in the following section.

Vignette 2: Percent overshoot for time response

A common introductory example to illustrate the effects of feedback features a second-order system with a unit-step input. The problem is often posed as a closed-loop system with negative-unity feedback and a plant transfer function that has an open-loop pole at the origin and a second open-loop pole at s = -a, where a is positive. As the plant gain K is varied from 0 to ∞, the output time response becomes increasingly more oscillatory, and the steady-state error, or difference between input and output, approaches zero. Illustrating these time response curves for varying K is a typical exercise early in the controls course.

This problem can be reformulated in terms of the damping coefficient ζ and the natural frequency ω_o. For the under-damped case, it can be shown that the percent overshoot for a step input (%OS) is a function only of ζ without dependence on ω_o. The formula for %OS is admittedly cumbersome; it is proportional to an exponential function of ζ and requires care in its calculation. The inverse problem that occurs in the design phase is even more complicated; the value of ζ for some given %OS is a natural logarithm divided by the square root of the sum of π^2 and the square of the natural logarithm term from the numerator.

Such harsh calculations can be avoided by using an approximate formula based on curve fitting to the exact formulas described above. Quadratic functions were fitted to yield approximate curves of %OS versus ζ and of ζ versus %OS with errors of only a few percent in both cases. This vignette provides a result applicable as well for tachometer or rate feedback for second-order systems.

This vignette shows how changing ω_o and ζ affect %OS in a second-order system. As an example of what a typical vignette provides for students, two figures are shown here. Figure 1 shows time response curves indicating that the %OS remains unchanged when ζ is set to 0.1 and ω_o is 2, 4, and 8 radians per second. Time response curves when ω_o was set equal to 4 radians per second and ζ was varied yielded data for Figure 2, which shows a curve of %OS versus ζ along with the approximate parabolic curve. To try this example, open the file changingz.mdl in Simulink.

Figure 1. Time response for constant ζ.

Vignette 3: Digital control: varying sample size

The time response problem for digital control systems is a particularly cumbersome one. A traditional approach to the problem is to apply z-transforms to form a pulse-transfer function of the plant preceded by a sampler and zero-order hold device. This step alone is formidable and requires particularly careful attention to detail. Forming and inverting the resulting closed-loop transfer function to obtain output response values at intervals of the sample size T is extremely unwieldy, relying on the students’ skills on z-transforms from a prerequisite signals and systems course. In a class of 30 students, experience has proved that it is likely that six or fewer obtain a correct solution to this homework problem.

A vignette based on Matlab simulations was developed to produce time response curves that demonstrate a decreasing stability, i.e., increased percent overshoot, as the sample size T is increased. Moreover, a look at a second-order system with this vignette showed that instability is reached for T at some value between 0.1 and 0.25 sec, whereas the corresponding continuous-time system remains stable for all positive gain K. Overlaying time response curves, shown for T = 0.05, 0.10, and 0.25 seconds in Figure 3, proved to be a very effective way of illustrating the key concept of this vignette.
Brief Remarks on Vignettes 7 and 8: Effects of adding poles or zeros

It is well known that adding left-half s-plane open-loop poles in the controller and plant feedback loop tends to make the closed-loop system less stable for many typical control system applications. For example, the positional servomechanism often used to introduce students to feedback control electromechanical applications is second-order when the electrical time constant can be neglected and third-order otherwise. The Routh table can easily be used to verify that the second-order system is stable for all positive gains $K$, but the third-order system has some sufficiently large $K$ beyond which instability occurs. Vignette 7 was developed to demonstrate this concept based on time responses from Matlab simulations.

Vignette 8 used Matlab simulations to demonstrate that adding left-half s-plane open-loop zeros tends to improve stability for many typical control system applications. Such situations occur when derivative control is present, e.g., in the use of PID controllers. Overlaying time response curves in both cases showed the desired results. These curves are not shown here due to conference page limits on papers.

Vignette 4: System sensitivity

This vignette demonstrates that a closed-loop system exhibits only a small sensitivity to variations in plant parameters. Figure 4 shows time response curves when the parameter “a” is varied in a plant equation given by $K/[s(s+a)]$. The middle curve is the base response when $a = 1$. The other curves show time responses for variations in “a” of ±10% and ±20%, i.e., for $a = 1.1, 0.9, 1.2,$ and 0.8. The middle curve is obtained for the base value ($a = 1$), the top curve for a −20% change in “a”, and the bottom curve for a +20% change in “a”. From this time curves, it can be concluded that percent overshoot increases and stability decreases as the denominator parameter “a” is decreased. On the other hand, percent overshoot decreases and stability increases when the denominator parameter “a” is increased. The gain $K$ was set equal to 1.

Figure 5 shows time response curves when the gain $K$ is varied in the same plant equation as for Figure 4. The middle curve is the base response when $K = 1$ (and $a = 1$). The other curves show time responses for variations in $K$ of ±10% and ±20%, i.e., for $aK = 1.1, 0.9, 1.2,$ and 0.8. The middle curve is obtained for the base value ($K = 1$), the top curve for a −20% change in $K$, and the bottom curve for a +20% change in $K$. From this time curves, it can be concluded that percent overshoot increases and stability decreases as the gain $K$ is decreased. On the other hand, percent overshoot decreases and stability increases when the gain $K$ is increased.

Observe that in both cases the change in stability is relatively small. The percent overshoot changed by only two percent for a change of ten percent in either the gain $K$ or “a” parameter. Thus, the system sensitivity is reduced for a closed-loop system configuration. These effects would become more noticeable if the base values of $K$ and “a” were larger. To try this example, open the file sensitivityb.mdl in Simulink.
This vignette demonstrates PID control by referring to an example in the class textbook by Nise [1]. Using both the uncompensated and PID-compensated transfer functions given in Table 9.5 of [1], box diagrams for each system were created in Simulink. From there, the transfer functions were imported into the Matlab SISO control system tool, which allows the student to create the root locus and Bode plots for any system. Figure 6 shows root locus and Bode plots for the PID-compensated system. To try this example, open the file PID.mdl in Simulink. Then open the SISO tool in Matlab and import the plant transfer function for both the uncompensated and compensated systems. The SISO tools contain interactive graphs that can be changed to optimize performance, create a compensator, or export an optimized system to Simulink.

Time response curves for the uncompensated and PID-compensated systems are shown in Figure 7. The PID-compensated system has the lower percent overshoot and faster rise time but a somewhat higher settling time.

**STUDENT SURVEY**

Students were highly positive for the most part about demonstrations in the classroom using Matlab simulations that show feedback effects and then having these vignettes available for hands-on evaluations outside the classroom. Table 2 shows student ratings on five vignettes.

<table>
<thead>
<tr>
<th>No.</th>
<th>*Rating: 5</th>
<th>4</th>
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<td>0</td>
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</tbody>
</table>

*5 = Highly Important, 4 = Very Important, 3 = Somewhat Important, 2 = Mildly Interesting, 1 = Not Important

Specific student comments on the positive side were:

- *The demos were very useful because we can quickly look at different characteristics of a system without working out the long, tedious mathematics.*
- *These demos give me different ways of approaching the same/similar problems.*
- *It provides a better understanding of the concepts.*
These are helpful in learning the material. It helps to actually see the effects of changing certain parameters, rather than just hearing about them.

It is useful to show how to calculate or estimate mathematic formulations that are difficult or impossible to do by hand.

They allow us to visualize what results we would get when working on Matlab.

I don’t think professionals would use pencil/paper over Matlab, so I don’t think we should either.

Student opinions to the contrary, at least in part, were:

They are useful but doing some harsh calculations allows you to be able to fully understand functions and what reasonable answers should be.
general, these teams worked very well together and made valid comparisons between the different controllers.

**Discussion**

A popular misconception in many controls textbooks today extending from several decades ago is that closed-loop systems can be analyzed fairly accurately by examining the dominant second-order closed-loop poles in the s-plane. It is demonstrated in several of these vignettes that the errors obtained from such approximations are much greater than previously acknowledged. A reliance on such approximations for either analysis or design considerations is unwise. Instead, Matlab simulations can easily provide time and frequency responses without inaccurate approximations. System errors that remain are due to plant modeling errors and/or unwanted disturbance inputs, not to unnecessary s-plane approximations.

Use of these vignettes to promote streamlined learning in a control systems course allows professors the opportunity to include easily materials on digital controls as well as other topics previously avoided due to an excessively crowded course. The argument that both continuous-time controls and digital controls could not be covered in the same course because of time constraints is disputed when using the vignettes described in this paper.

An important by-product of this approach is that the controls course can be taught more easily by other professors who are expert in related areas of electrical and computer engineering and are only peripherally interested in feedback principles. The portability of this approach to other systems courses and its value especially for programs having smaller numbers of faculty members who must cover several related systems courses in the curriculum is also evident. Yet, the overriding importance remains the potential for enhanced learning for students in all system courses.

Finally, other motivations for developing these vignettes were (1) experiences with the author’s own detailed Wiley textbook of 20 years ago [4], (2) observations as an ABET EAC program evaluator during over 20 visits on the difficulty of departments with small numbers of faculty in teaching the controls course, and (3) knowing that other professors in my home department with different but related interests may sometime be assigned to teach the basic controls course.

**Conclusions**

Based primarily on Matlab and Simulink, several vignettes were developed to promote improved learning in a feedback controls course being taught to senior electrical and computer engineering students. Four of the vignettes were described in some detail in this paper, and another two received some discussion. Student surveys indicated that the students were highly positive about the streamlined learning approach for the selected control systems topics covered by these vignettes. Other advantages include demonstrating the effects of digital control, viewing time responses for random disturbances, and pinpointing some of the limitations of traditional second-order dominant s-plane closed-loop pole approximations in feedback systems analysis and design.

**References**