

AN INTERACTIVE LEARNING TOOL FOR DYNAMIC SYSTEMS AND CONTROL

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ABSTRACT

Although there are many stimulating and practical applications for system dynamics and automatic control, students often find the material too abstract, too mathematical, and difficult to master when it is presented in lectures. The difficulties experienced by students in learning system dynamics and controls include the following: (1) Dynamic and control systems are interdisciplinary in nature and require complex mathematical expressions that were taught in previous courses. (2) Computer simulation and hands-on experiments are necessary in order for the students to fully appreciate the basic concepts of automatic control. (3) Lecture hours are insufficient to provide both the theory and real-world applications of system modeling and automatic control. In order to overcome these problems, an interactive multimedia software tool that allows the students to explore the design space was developed. We discuss here the role of technology as it can be applied in teaching system dynamics and control. The primary goal of this work is to build a tool that assists students in learning system dynamics and control by providing a link between control system design (CSD) theory and laboratory learning. Specifically, the materials developed provide support in three different forms of instruction; labs, lectures and homework.

1. INTRODUCTION

System dynamics and controls have played a vital role in the advancement of engineering, science, modern manufacturing, and mechatronics. They provide a comprehensive treatment of the modeling, analysis and design of continuous-time and digital control systems. Although there are many stimulating and practical applications for system dynamics and automatic control, students often find the material too abstract, too mathematical, and difficult to master. The common problems experienced by the students in learning system dynamics and controls include the following: (1) Dynamic and control systems are interdisciplinary in nature and require complex mathematical expressions that were taught in previous courses. (2) Computer simulation and hands-on experiments are necessary in order for the students to fully

appreciate the basic concepts of automatic control. (3) Lecture hours are insufficient to provide both the theory and real-world applications of system modeling and automatic control.

Dynamic systems and control education in a typical mechanical engineering (ME) program consists of two basic courses: System dynamics covers basic materials for modeling and analyzing dynamic systems of an inter-disciplinary nature, and automatic control presents techniques for analysis and design of control systems. In the Woodruff School of Mechanical Engineering at Georgia Tech, these two courses are titled system dynamics and automatic control. The prerequisites for system dynamics are courses in introductory differential equations, circuit analysis, and mechanics. The prerequisite for automatic control is a course in system dynamics. A survey conducted by the first author during the 1992-1993 academic year in the School of Mechanical Engineering at Georgia Tech has indicated a relatively high attrition rate (D, F, and W) of senior-level students participating in an automatic controls course. Since then, faculty in the ME department's Automation and Mechatronics Research group discussed ways to improve the students' performance. The faculty group sensed that although students conducted experiments related to system dynamics and controls in the existing curriculum, the students could learn substantially more from the lab courses.

How closely should laboratory courses be tied to "theory" courses? When the purpose of the lab is to teach experimentation, one viewpoint was that a "vertical laboratory program" should be implemented in a way that is nearly independent of the theory courses. This kind of laboratory operation has proved to be efficient and cost-effective. This efficiency, however, has largely been achieved at the expense of the link between laboratory and theory, which is essential in learning dynamic systems and control. For this reason, we have developed an interactive multimedia approach, which will take maximum advantage of the laboratory experience and of full-motion video to improve students' comprehension of dynamic systems and control by directly relating the course materials to labs. There is a need for educational technology to achieve the following objectives: (1) to improve dynamic visualization by incorporating illustrative application examples and laboratory

practices in lectures, (2) to provide a self-directed learning environment, and (3) to expose the essence and significance of mathematical expressions more effectively in laboratory examples.

Over the past ten years the confluence of digital technologies has made it possible to provide a fertile environment to support the instruction of students in many domains. Critics of computer based training (CBT) cited that there were really no significant differences between traditional classroom instruction and the use of technology for instruction [1]. Others have shown that students learn and retain more when they can “see” the concepts in addition to just reading or hearing about them [2]. In evaluating software, it would seem to be more pertinent to look at things such as efficiency, cost effectiveness, consistency of instruction, and the overall effectiveness of the instruction. We explored in our early work [3] utilizing some parts of the mechanism proposed by Reeves [4] to develop an interactive tool to support teaching of system dynamics and controls in several different forms. Aiming at bridging the gap between lecture and laboratory learning, we tested the computer-aided-instruction primarily in two areas; namely, classroom presentation, and electronic assessment of laboratory studies.

In this paper, we discuss the development of self-assisted review sessions. The multimedia software will go far beyond the material in traditional textbooks by illustrating key concepts in dynamic systems and control through video display, animation and active exploration. It incorporates video, voice illustration, and hands-on simulation. This instructional design enables the student to have more control over their learning processes than traditional methods of learning provide. One of the objectives is the use of computer interaction to enhance problem-solving techniques. By answering questions, the students are guided through a proposed solution strategy of a real world problem.

The remainder of this paper is organized as follows: Our approach for improving the effectiveness of learning is described in Section 2. The software is described in Sections 3 and followed examples in Section 4. Finally, we summarize our observations and conclusions in Section 5.

2. OUR APPROACH

In the Woodruff School at Georgia Tech, the sequence of the basic courses in system dynamics and controls are structured as shown in Figure 1. ME3115 System Dynamics deals with modeling techniques for analyzing dynamic systems of an interdisciplinary nature, and ME4445 Automatic Control presents design and analysis techniques of control systems for improving system performance. In parallel to the theory courses, the lab sequence is ME3056 Experimental Methodology; ME4052 Mechanical Systems Laboratory; and ME4055 Experimental Engineering. ME3056 is the junior-level instrumentation course and ME4052 allows a more in-depth

study of selected mechanical systems. In ME4055, students work in teams on a quarter-long project.

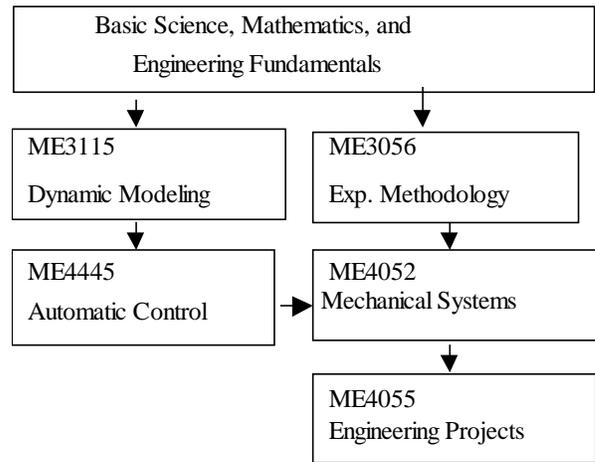


Figure 1. System dynamics and controls course structure

2.1 Pedagogical Justification

Pedagogically, the CSD software draws on constructivism, cognitive apprenticeship, and drill and practice activities [5] - [7].

The CSD software draws on cognitive apprenticeship in that it promotes learning from a project rather than isolated problems. Time spent learning the multifarious concepts surrounding control systems design is not enough to promote retention of the material. Instead, the student must be actively engaged in solving a problem in an environment similar to that of professional control system designers. Real-world problems interlace both the lesson and activity components of the software. For example, the Root Locus Design method is presented and explained within the context of a magnetic levitation train problem. The students are asked to take on the role of the controls engineer who faces the task of ensuring that the train remains suspended while passengers board and depart the train.

Cognitive apprenticeship may also be viewed in the way we treat the MATLAB® exercises. Students are linked to completed MATLAB® programs in which they may enter values into a field to study the performance of their system. Students may access to and the manipulation of the MATLAB® code so that they may begin using MATLAB® independently of the CDS software. As the students become more familiar with MATLAB®, s/he will become less dependent on the pre-built MATLAB® programs and rely more on her/his ability to write MATLAB® code.

The CSD software is constructive in that the material is structured to be easily grasped by the student. For example, the design method into lesson topics that closely represent an expert's understanding of CSD while ensuring that the structure is not so complex that it cannot be easily navigated. Further,

although much of the software is presented linearly, the students are allowed to page ahead and back allowing an overall view of the structure of a particular concept or procedure as could be done with a book.

Finally, the CSD software contains drill and practice components designed so that the student may check his/her answers and internalize the structure of certain procedures.

2.2 How does the student know how well s/he is doing?

Although feedback and guidance are provided for each question individually, we adhere to the constructivist notion that students are more motivated when they are left to gauge their own performance. For this reason, students are not provided with a tally of the total responses they have made that are correct or incorrect. We wish for the students' goal to be the design of a controller that works rather than a myopic and removed goal of getting ten out of ten correct. With this, we provide the students with all the tools they will need to know whether their design works or not.

3. SOFTWARE DESCRIPTION

The interactive learning environment was created using Authorware®, a package designed for authoring interactive courseware. The simulation programs were done in Matlab® and animation was created using Working Model®. Authorware allows the user to shell out of the host program to execute MATLAB® simulation programs. Figure 2(a) shows the overall functionality of the CSD software. This screen capture is taken from the software overview section designed to familiarize students with the software. There are five general areas to note; namely, the *title bar*, the *lessons menu*, the *activities menu*, the *content area*, and the *tool bar*.

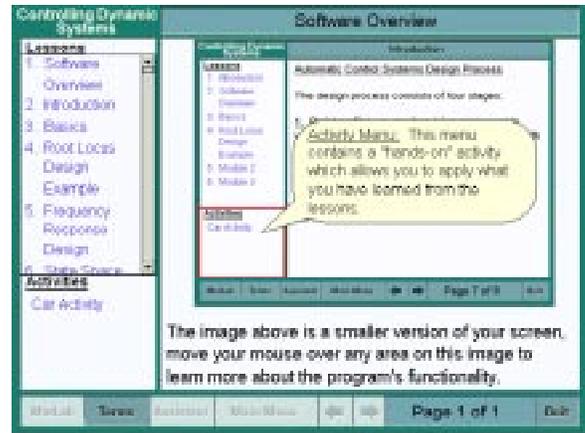
The *lessons menu* is a hypertext list of the lessons available to the students. The broad hypertext sections lead the student to more specific topics. For example, "Root Locus Design" leads the student to the sub-topics, "Modeling," "Analysis," and "Design" which then lead the student to specific lessons under these sub-topics. The current implementation illustrates only root locus design but we plan to add frequency and state-space design also.

The *activities menu* is also a hypertext list of available activities. This area is expandable to accommodate other activities, all of which lead the student through an extended design problem.

The *content area* is the large area in the middle and right of the screen. This houses the content and interactions of each lesson and activity.

The *toolbar*, Figure 2(c), along the bottom provides students access to various tools (such as MATLAB®, a glossary of terms, and a built-in assistant) and allows them to navigate through the material. This toolbar also allows the student to navigate vertically and horizontally through the material; the

main menu will take the student up to a higher level view of the available lessons while the previous and next arrows allow the student to page through the content of a specific lesson or activity. Notice also that the "Assistant," "Previous," and "Next" arrows are shaded to indicate that they are not available.



(a) Screen shot of software overview



(b) Title bar



(c) Toolbar

Figure 2. Various sections of the CSD software

4. EXAMPLES ON ROOT LOCUS DESIGN TECHNIQUES

The organization of the hypertext concepts for illustrating the Root Locus Design method act as a type of semantic net [8] [9] in which CSD is portrayed as we wish our students to understand it. Although there are as many different semantic representations of the CSD knowledge domain as there are experts in the field, the following representation of the design method is the most expandable and transferable for students at Georgia Tech.

- Problem statement and design specifications
- System modeling and linearization
- Controller design with stability, steady-state and transient analysis)
- Simulation and implementation of the closed-loop system

We discuss two examples: The first example is the root locus technique to design a magnetic levitation control system. In the second example, the students are asked to design a regulator to maintain a specified distance between two moving cars.

4.1 Magnetic Levitation

Figure 3 illustrates an (actual) laboratory setup on magnetic levitation that challenges the students and requires them to apply

the control system design theory that they learned to solve the problem. This setup utilizes components that our students have learned in their co-requisite ME3056, which includes an LVDT, a power amplifier, and a personal computer with A/D and D/A converters. The schematic includes hypertext that allows the students to review the fundamental of the instrumentation involved.

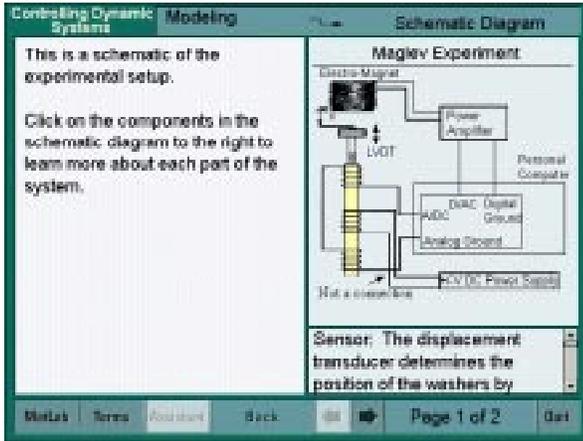


Figure 3. Screen shot illustrating the experimental setup

To engage the students in actively in solving the problem, we pose the design problem and specifications as follows:

Typical problem statement:

The train system on the right (not shown in this paper) runs through a tunnel. Along the ceiling of the tunnel are electromagnets that attract the train. These electromagnets pull the train up with enough force to keep it suspended but not with so much force that the train attaches itself to the electromagnets on the ceiling. Visualize that you are currently working on a project in which you have to control the train's suspension while people are boarding. Passengers board from a platform, and the train needs to compensate for each person who steps onto and off of the train. You are asked to test the design concept of a computerized regulator system using a laboratory prototype (see Figure 3). The objective is to suspend the train at a prescribed level using electromagnets with position feedback.

Typical design specifications:

The vertical position of the train is measured by a position sensor whose output is compared with the desired position entered from a keyboard and processed in a micro-computer. The electromagnet is thus controlled in such a way as to move the train vertically to the desired position. A more detailed figure of a scaled-down prototype system for the proposed concept is shown in the figure to the right (not shown in this paper). The system must be designed so that it is insensitive to the change of passenger load or other extraneous signals or noise during operation. The design specifications are as follows:

- (1) The steady-state error is zero.
- (2) Maximum overshoot must be less than or equal to 5%.
- (3) The 1% settling time of the system must be less than or equal to 5 seconds.

Typical tasks are as follows:

- 1) Derive a model to describe the dynamics of the cargo, which describes the time-dependent position as a function of current and input disturbance caused by the change in passenger load.
- 2) On the basis of the model derived in task 1, analyze the system with position feedback to determine whether the system meets the design specifications in terms of stability, transient and steady-state responses.
- 3) Improve the system by designing an appropriate control law. Information on the velocity of the cargo in the vertical direction can also be processed by the micro-computer from the position data so that the system is stable and the time-dependent position of the cargo can be better controlled.
- 4) Simulate and implement the controller. Evaluate its performance.

System modeling and linearization

From the Newton's second law of motion, we have

$$m \frac{d^2 x}{dt^2} = f_i + mg - f(i, x) \tag{1}$$

where m is the cargo mass without passengers; i is the current flowing through the electromagnet; f_i is the unknown passenger load; and $f(i, x)$ is the non-linear magnetic force.

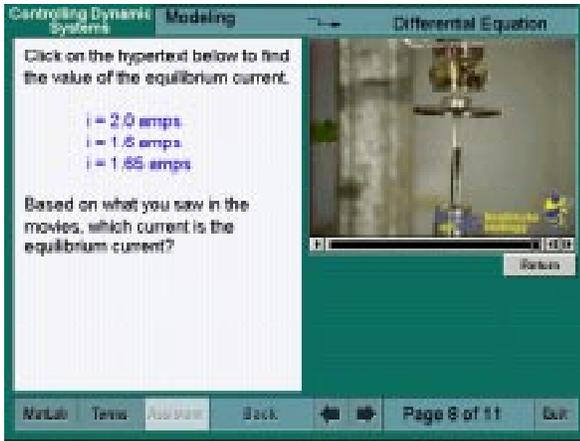
In this problem, the students are asked to derive a linearized differential equation for the system about the desired steady-state operating position. The linearized equation is in form:

$$m \frac{d^2 z}{dt^2} = az + bi - f_i \tag{2}$$

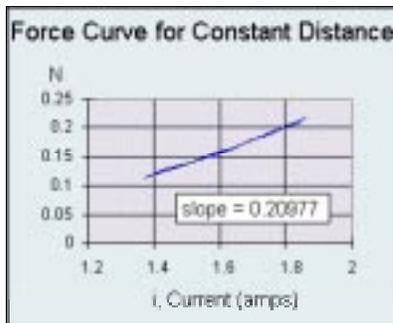
where $z = \bar{x} - x$; $u = i - \bar{i}$; $a = \left. \frac{\partial f(i, z)}{\partial z} \right|_{z=0, i=\bar{i}}$;

$b = \left. \frac{\partial f(i, z)}{\partial i} \right|_{z=0, i=\bar{i}}$ and f_i is treated here as a disturbance.

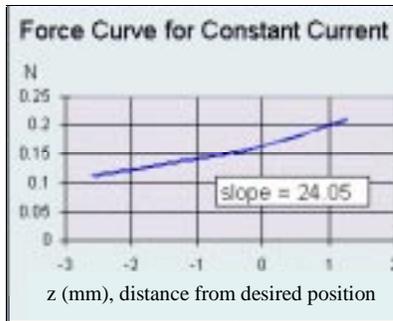
Several mini-video series are in the software to illustrate the experimental process of obtaining sample experimental data as shown in Figure 4(a). Given the sample experimental data about a steady-state operating point as shown in Figures 4(b) and 4(c), the students are asked to take an active role in using the experimental data to derive a linearized model for the system.



4(a) Video illustration



4(b) Static force-current relationship (constant spacing)



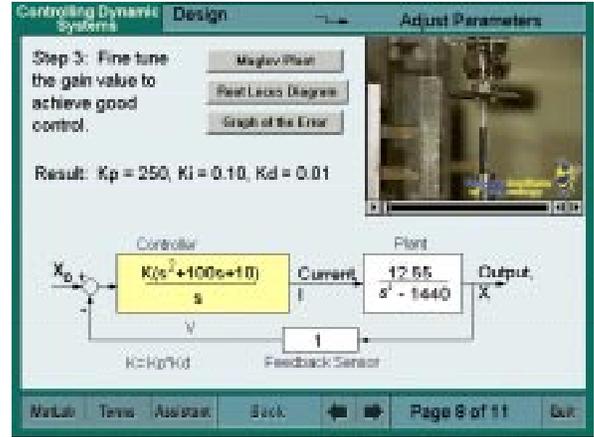
(c) Static force-displacement relationship (constant current)

Figure 4 Linearized experimental model

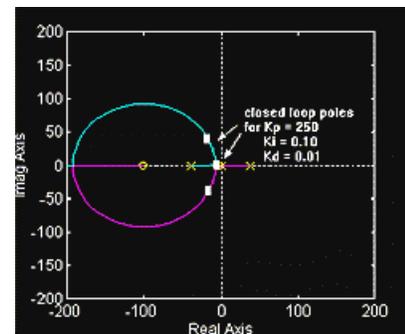
Controller design

The linearized system model is open loop unstable with an unknown disturbance. Students are asked to explore the effects of the proportional (P), derivative (D), and integral (I) actions on the system in terms of stability, steady state and transient performances. The guided design example begins with the open loop system, then adds proportional feedback, next includes the derivative action and subsequently an integral action, ultimately leading to the design of a PID controller. In each of these steps, the design process explains the choice of the controller and the students are asked to predict the stability, steady state, and transient responses analytically. Detailed steps are embedded in the *Assistant* toolbar to assist the students when needed.

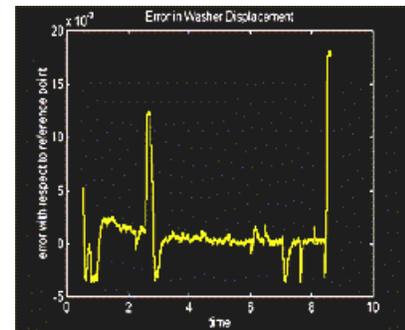
Figure 5(a) shows a screen shot of the guided design example, which provides the students a means to compare their analysis with pre-recorded video clips of experiments for several selected PID gains. Figures 5(b) and 5(c) show the corresponding root locus plots and position errors under the effect of an external load.



5(a) Screen shot of a typical guided example



5(b) Root locus plot



5(c) Typical position error plot with disturbance

Figure 5 Controller design

Simulation and implementation of the closed-loop system

With a series of pre-recorded video clips, we illustrate the development of an experimental setup, which is, however, characterized by a different set of parameters. The students are asked to provide their own controller design and predict the performance by simulation.

4.2 Car Activity

In the second activity, the student is given another problem as shown in Figure 6 and asked to apply the technique illustrated before. As in the previous problem they are guided to a solution with the level of support required in terms of the tools needed to solve the problem as illustrated in Figure 7.

We incorporate into the instructional design questions designed to provoke reflection about what they have learned, which encourages the students to think about the topic on a deeper level. We believe that students learn and retain more by doing but they learn even better when they subsequently tell about what they have learned [6].

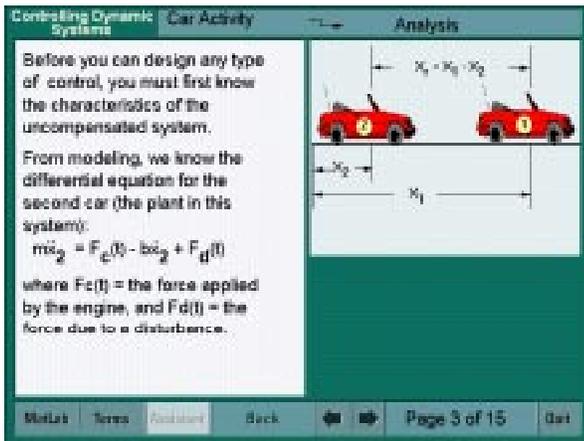


Figure 6 Example problem

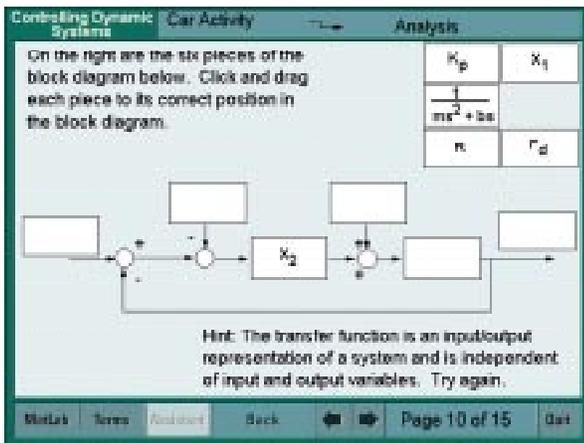


Figure 7 Example question asked

5. CONCLUDING REMARKS

In summary, we present here a solution to address the problems students encountered in learning system dynamics and control. Specifically, we bridge the gap between theory and laboratory learning through the use of interactive multimedia software in three different forms, namely, labs, lectures, and homework in a sequence of courses. The concept feasibility

was demonstrated. Future research is being planned to address the following questions for implementing CAI as a cost effective tool for instruction: (1) What is the cost-effectiveness of multimedia-based pedagogy for instructing system dynamics and control? (2) What is the impact of the instruction? (3) What are the effective user interface metaphors and models?

The use of these electronic technologies in engineering education is not yet widespread and the full effects and capabilities are yet to be documented. The authors plan to implement and evaluate the system described in order to further refine and enhance its capabilities.

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