Some Experiments in Dynamic-Simulator-Based Control Education

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Abstract
We are developing six control engineering design modules for use by graduate students, advanced undergraduates, and practicing engineers in learning about process control. This is part of a larger project investigating the use of dynamic simulation and visualization to enhance the education of manufacturing engineers, technicians and operators. The crucial motivating ideas are that active learning can substantially enhance education—a widely accepted idea—and that computer-based dynamic simulation and visualization can induce active learning.

The modules cover the fundamentals of control engineering as well as an introduction to run-to-run control. Each module requires the student to interact, in real time, with an animated illustration of the process to be controlled or the control concept being discussed. The next step is the evaluation of the effectiveness of this teaching tool.

1. Introduction
We are developing six control-engineering modules as part of a larger project entitled "Simulator-based manufacturing education and training for microelectronics processing." The goal of this project is to develop, demonstrate, assess, and refine a new approach to manufacturing education and training. This approach is based on active learning experiences provided by computer-based dynamic simulation and visualization. It is organized as a collection of related modules, each one having a specific educational goal. Another important feature of this project is that it has a very broad target. Individuals ranging from experienced professionals through graduate and undergraduate students and including technicians are expected to benefit from the same educational modules.

The basic structure of the control design modules is determined by the principles underlying the broader project. Although the ultimate aim is more general manufacturing, the focus of this project is semiconductor manufacturing. These manufacturing processes have very complex physical and chemical interactions, which can be difficult to explain to the student. This suggested the use of dynamic simulation and visualization to assist students in developing a useful understanding (metaphors in the educational jargon) of these complex processes. To facilitate this, the simulators are required to accomplish four goals:

1. Realistically reflect physical and chemical behavior as embodied in equipment and processes.
2. Present that behavior to the learner effectively through appropriate and advanced means of visualization.
3. Enable direct interaction between learner and simulator, whereby the student may directly alter the design and status of equipment and process, observe the consequences, and learn.
4. Adapt to individual and systematic actions of the learner to provide and reinforce his ability to perform effectively.

Of particular relevance to the control modules are the following properties of the dynamic simulators, both of which are logical consequences of the four goals. First, the simulators must respond naturally and correctly to student actions. Second, the system responses are shown dynamically—in real time and at the
rates of response dictated by physics and
chemistry.

There are six control engineering design mod-
ules. In each, the computer screen is divided
into three windows, as in Fig. 3. The upper left
window shows a representation of the process.
For example, a pressure control process is il-
lustrated by an animation of a pressure cham-
ber, including an Archimedean screw inside a
cutaway drawing of a pump, as shown in Fig. 1
below. The screw rotates when the pump is
active. The upper right window shows a
graphical representation of the relevant process
variables, as might be shown in a meter or
gauge when this is appropriate. The lower
window, the guidance window, contains text.
It suggests things to try, raises questions to try
to answer, and provides feedback to the stu-
dent. In every module, in order to enhance the
students’ engagement with the material, stu-
dents are asked to compete with the automatic
controller they are designing. For example,
they are asked to manually control the same
process and their performance is displayed
along with that of the automatic control. Be-
sides involving the student, this competition
motivates and enhances our discussion of
evaluation of controller performance and pro-
duces additional insight into the operation of the
controller, as will be explained in more detail
subsequently.

The first module is entitled Introduction to
Control. It begins with a display of a tank
filled with a blue fluid (water) at the upper left,
as shown in Fig. 2. There is a user-controlled
valve controlling the flow of fluid into the tank.
There is another valve at the bottom of the tank
controlling the exit of fluid from the tank. The
upper right window contains a meter displaying
an analog display of the height of the fluid in
the tank. The text window briefly discusses the
set up and then asks the student to try to keep
the level of fluid in the tank as constant as pos-
sible. The simulation complicates this in two
different ways. First, by randomly opening the
exit valve for just long enough to empty the
tank. Second, by randomly opening the exit
valve for

![Figure 2: The tank display, including the automatic controller in operation. Note the overflow protection.](image)

brief periods. When the student is ready, a
float valve is added to the animation at the up-
per left. The guidance window explains the
purpose of the float valve and proposes some
ways to compare the performance of the stu-
dent with that of the automatic controller. Af-
ter these comparisons are completed and ana-

Figure 1: The pressure chamber as displayed
lyzed, the image in the upper left screen changes to that of the pressure vessel described previously. The other windows change similarly and the student begins an analysis of the control of pressure in the context of semiconductor manufacturing. In fact, the control of the water level in the toilet tank and the control of the pressure in the pressure vessel are very similar. Despite the large differences in appearance, purpose, and complexity, the dynamics and the controller are virtually the same.

The effects of feedback gain changes, set point changes, and plant variations are all studied in the context of pressure control. The last portion of this introductory module deals with modeling and block diagram notation.

The titles of the six modules are:
1. Introduction to Control
2. The PID Controller and its Tuning
3. The Advanced PID Controller
4. Run to Run Control
5. Linearization and Linear Systems

The remaining five modules are described after a brief review of related work.

2. Related Work

Very similar ideas have been implemented in a collection of interactive control education modules developed at Lund University in Sweden. The article "Dynamic pictures and interactive learning" [1] could virtually serve as a prospectus for our efforts. Our modules on linear systems and on classical control design were greatly influenced by the earlier similar modules described in the article by Johansson et al. [2]. The major differences between the work reported in those two articles and ours are (a) their target audience is much narrower than ours—upper level undergraduates and graduate students studying control (b) the details of the modules are different in the same way that textbooks covering similar material often are. Both of those articles contain a wealth of references to other work on the use of the computer to enhance control education.

Another particularly notable effort is described in [3]. Crutchfield and Rugh have developed eleven interactive modules illustrating various aspects of linear system theory. The interactivity and playfulness of these modules is similar to what we are trying to achieve with ours. The target audience is much narrower than ours—undergraduates taking the first electrical engineering course in signals and systems.

3. Other Modules

The module on the PID controller and its tuning begins by having the student compete with a well-tuned PID Controller in controlling a simple process. On the first attempt, the student is only given a meter display of the output—the instantaneous value of the signal. He is asked to control a plant, effectively acting as the gain in a pure proportional controller. His performance is compared with that of a good proportional controller. On the second try, the student is given an oscilloscope trace that includes the past of the output. Here the comparison is with a PID controller. These displays are used to enhance the student's appreciation of the role of each of the terms in the controller.

Tuning the controller is first studied by instructing the student to be more or less aggressive. For example, when only the meter display is available, trying harder to keep the errors small effectively increases the student's feedback gain. By choosing the process carefully, we are able to demonstrate that trying too hard (too high a feedback gain) can cause instability. Robustness is also addressed by varying the plant. Note also that the use of different performance metrics emphasizes different aspects of control. Finally, the students are given a realistic plant and PID controller to tune in real time. They are given advice on how to tune—measurements to take and how to use them.
The advanced PID module addresses anti-windup controls, the use of PID controllers for atypical plants (such as those with lightly damped resonant poles), the use of separate gains for input and feedback, and other features of real modern PID controllers. Again, we begin by having the student manually control the plant. We force them to drive the input into saturation and experience the loss of control that this creates. We also introduce them to the basics of step, impulse, and frequency response.

The run-to-run control module deals with a topic of great importance in manufacturing control that is relatively unknown among the control community. The issues are to detect changes in the plant due to wear and adjust the controller to compensate for them. Again, the module sets up a competition between the student and the automatic controller and uses this competition as a vehicle to teach the student about the issues involved in designing and implementing the controller. For instance, the student learns about the role of observation noise in complicating the detection of changes in the process by noticing the effect of such noise on his or her ability to detect changes in the process.

The linearization and linear systems module begins with a simple illustration of linearization similar to the one in [1 & 2]. This is elaborated by a non smooth example, an ideal saturation. Tests for linearity, such as coherence, are introduced and studied experimentally. That is, the response of the linear model is compared to the true response.

The question of representation of linear systems is studied first by having the computer add up step responses to approximate the true response. This representation as an approximate sum of steps is gradually morphed into a representation in terms of the impulse response. Representation by exponentials is handled similarly. We start with sinusoidal approxi-

4. Conclusions and Further Work

The next phase of this project calls for the evaluation of these dynamic simulation and visualization-based educational modules. They will be tested for their effectiveness in several different roles. We are interested in their use to train technicians in how to operate and tune control systems used in semiconductor manufacturing. We are also interested in their use as a supplement to the course material in undergraduate controls courses. Finally, we are interested in their utility as intuition builders for graduate students studying controls. Of course, not every module will be an effective teaching tool for every one of our possible users. However, it is often true that technicians and graduate students would both benefit by knowing more about each others areas of expertise. We believe some of these modules achieve this.

The results of the tests will be used to revise and improve the modules.

5. Acknowledgement

This work is supported by the National Science Foundation under grant EEC 96-96212.

6. References


Figure 3: The overall display shown to the student.