INVENTING MULTILOOP CONTROL SYSTEMS IN A JIFFY WITH INTERACTIVE GRAPHICS

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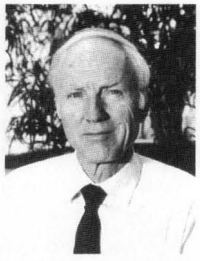
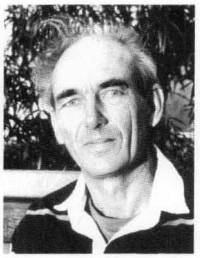
Inventing multiloop control systems isn't easy—especially multiloop systems for chemical processes. That's the usual task facing us as chemical engineers; attending to the regulation and coordination of many variables is what makes the task difficult.

For example, consider being presented with a challenge to synthesize a control system (and to demonstrate that it works!) for the little process shown in Figure 1. The distillation column in this process is to produce a top product with impurity not exceeding one percent, and it must do so during production rate changes requested by the sales force and during unexpected appearances of a reaction-rate inhibitor in the reactant feed to the CSTR. But that's not all: during such process upsets and production-rate changes, the reactor must be guarded against overflowing and the distillation column must not be allowed to flood or weep. There are eight valves and twelve measurements.

What to do?



Exploring new approaches to educating students in process control systems has been a major activity of ***Alan Foss*** *in recent years. These new approaches are coming to flower now, thirty years into his teaching career at Berkeley. Prior to his Berkeley years he practiced engineering with the DuPont Company. He studied chemical engineering at Worcester Polytechnic Institute and the University of Delaware.*



Peter Goodeve *is a software development engineer and consultant at UC Berkeley and with other organizations. He received a BSc degree in psychology from University College London and an MS in human factors engineering from UC Berkeley. His particular computer programming expertise includes real-time control and the development of efficient user interfaces.*

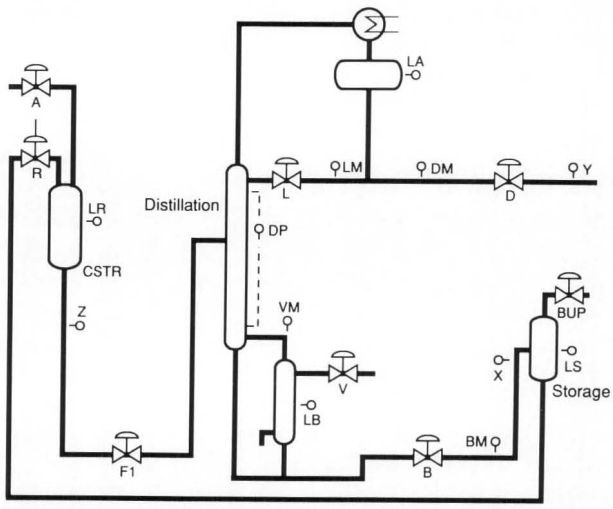


FIGURE 1. *Diagram of a reaction and separation process used as a three-week project in control system synthesis and implementation. (Computer display redrawn to meet publication quality standards.)*

Our undergraduate students need to encounter this sort of challenge. It serves as a superb exerciser of their inventive talents—and talents they have. It is not heresy (is it?) to assert that inventive talents ought to be exercised somewhere in the curriculum? Our observation has been that students are just "itching" for this sort of opportunity after learning something about control-system concepts.

Two of our students, for example, teamed up at the tail-end of our process control course and created the system shown in Figure 2. They reckoned that they would reduce the demands on the column control system by holding a reactor conversion reasonably constant through adjustments in the residence time. The column overhead control system employs an interesting structure that produces a D/V-ratio as the output of the top product concentration controller. This system also guarded against column

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flooding or weeping by incorporation of an override system to hold column differential pressure within high and low limits. An override feature also keeps the reactor from overflowing, they say.

In their report, the students said that they also tried a couple of feedforward links, but did not incorporate them into the final system because the links did not contribute much to the system's performance. Their report showed scores of system transients displaying the performance of the controlled process in the face of production rate changes and the appearance of the reaction inhibitor.

We have presented this piece of student work simply to display the capability that is available to students with this program. We dare not attempt any deeper explanation of the workings of this team's control system.

All of the above did not just spring into the students' heads as they first sketched out their thoughts about the system. It took several trials over a period of two weeks. Trying and testing must therefore be efficient and speedy.

Time is even tighter in a 3-hour laboratory. There, students have to develop control systems in tens-of-minutes, not days. We have attempted to enhance both efficiency and speed by developing a computer program that permits a student to develop a diagram of a control system configuration on the screen of an IBM AT or a PS/2 personal computer. We call

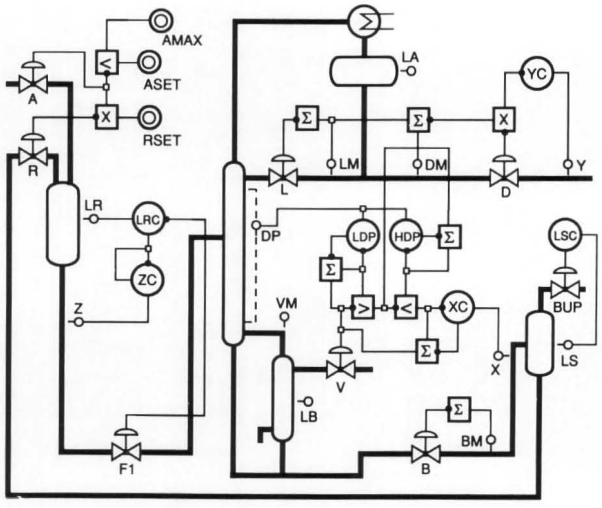

FIGURE 2. Students' control system: Configuration to regulate product quality and reactor conversion while guarding against reactor overflow and insuring that column operation is held within flooding and weeping limits. (Computer display redrawn to meet publication quality standards.)

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this new program UC SIGNAL. It affords a rapid means of configuring the signal paths in multiloop control systems. The control system structure output by the program can be introduced into our real-time computer control program UC ONLINE and executed either on simulated processes or on laboratory apparatus. The features of UC SIGNAL and its contribution to process control instruction is the subject of this paper.

ENHANCING THE PROCESS OF INVENTION

There are two steps in the invention process: system configuration and testing. An exercise in configuration only is not satisfactory because the student will not know whether his system is workable or how well it will perform. It is essential that there be a means to test system workability and that it be immediately available. The immediate feedback of facts about workability and performance is an essential ingredient in making the invention process speedy.

THE CONFIGURATION STEP

We prepare a diagram of the process under consideration, such as the one in Figure 1, and display it on the computer screen. The diagram corresponds to a process simulation we have prepared or an apparatus in our laboratory. Students thus work directly with a pictorial representation of the process. The drawing of control loops is done automatically on the diagram in response to the student's declarations of the links he wants to make between measured and manipulated variables and the control elements he wants to incorporate in those links. The act of drawing the control-system structure on a diagram of the physical process (as distinguished from a conceptual abstraction) focuses the student's attention on the functionability of the control loops and the contribution they can make to the workability of the process. The visual association of the control system with the process equipment is an important and subtle element in the invention process.

Just how the student arrives at the control-system structure that he sketches is as varied as the

individuals in the class. Most subject the uncontrolled simulation to step inputs through use of our program UC ONLINE, then observe the behavior of the several variables and form a cause-effect mental model. Many of them attempt (after prompting) "manual" control before settling on their first configuration. Others carry the analysis deeper by fashioning empirical quantitative representations of the responses, which are then used in a linear-system analysis and design package (*e.g.,* the program "CC" by Systems Technology, Inc.) to learn something about the underlying dynamic characteristics of the process or parts of it. The relative gain array, if it can be obtained readily, may be of some assistance when thinking about proposed configurations. Our students' decision to use a D/V-ratio in the distillation overhead system was derived from such an RGA analysis. (We have a module associated with our distillation simulation that makes the RGA analysis for the column effortless.) One can, of course, direct students to still other analytical tools if the students have been prepared for them and if computing capability is available.

THE TESTING STEP

For control systems as complex as the one illustrated in Figure 2, the testing step is essential (at least for the student, and also for the instructor who has to be convinced of the workability of some of the labyrinthine systems). Without a demonstration of the workability of a control system and an investigation of its performance, the invention is incomplete.

This step is also essential for even the simplest control system, because inexperienced designers may not be able to think through their designs with perfect clarity. And the testing capability has to be immediately available and easily executed; otherwise reticence to use it will surely build with time as the designer gets further and further into his system development.

We feel that it is important that the system used to implement the control system be interactive, either in real time (with laboratory apparatus) or in scaled time (with process simulations). A system with such capability allows the student to observe the evolution of process variables, to debug and commission loops one by one, and to make changes in process disturbances, setpoints, tuning parameters, controller status, etc., in real time.

Students in a first course in process control should not be expected to develop a first-principles model for a process that is as involved as the one shown in Figure 1. Most could not do it, and even if they could the exercise would not be an appropriate use of their time. A course in process control should be focused primarily on the systems problems that need to be solved in carrying out process operations. Therefore, we prepare the process model for the students. The models are then immediately available for testing a control system. They can be (and usually are) nonlinear, they can be "noisy," and they can display variations in static and dynamic character simply through changes in throughput rate. Models can be written in Fortran or C, or even fashioned by using some of the dynamic elements of our multiloop control program. Several undergraduate students have assisted us in developing these models.

The testing phase is accomplished with our interactive multiloop control program UC ONLINE.[1] We are presently using a considerably enhanced version of that program.

LITTLE CHALLENGES AND THEIR SEQUENCING

Of course, students cannot jump into a project such as the one illustrated in Figure 1 without some preparation. We accomplish this with a sequence of laboratory projects and homework assignments of increasing sophistication over the course of the semester. All of our laboratory apparatus can be operated with any of several objectives in mind and any of a number of control system configurations.

We start very early in the semester (third week) by requiring that students use UC ONLINE to access measurements of laboratory process variables,

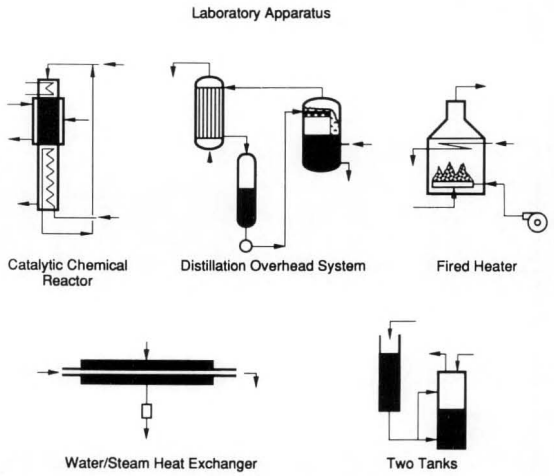

FIGURE 3. *Simplified diagrams of laboratory apparatus used for student exercises on multiloop control systems.*

convert them to engineering units, and display them in real time on the computer screen. They also connect output signals to valves and make changes in the flows with keyboard commands for the purpose of observing the process response to those flows. No computer programming is involved in any of this. Simplified diagrams of the apparatus in our laboratory used for such exercises are shown in Figure 3.

The students are subsequently introduced to UC SIGNAL, which they then use for the rest of the semester to develop control-system diagrams for the laboratory equipment and process simulations. Diagrams of some of our simulated processes are shown in Figure 4.

The sophistication of the control-system configurations in both activities evolves over the semester, starting with single feedback loops and moving on to cascades, feedforward, feedforward-feedback, 2 or 3 loops, gain scheduling, auctioneering, overrides, and variable structure systems. The experience is just right to whet their appetites for projects such as the one in Figure 1.

CAPABILITIES OF UC SIGNAL

UC SIGNAL was designed to aid students in stating their ideas for a process control system as quickly as possible. Our intention was to make its workings as close as possible to what one would sketch on paper and as free as possible of the endless

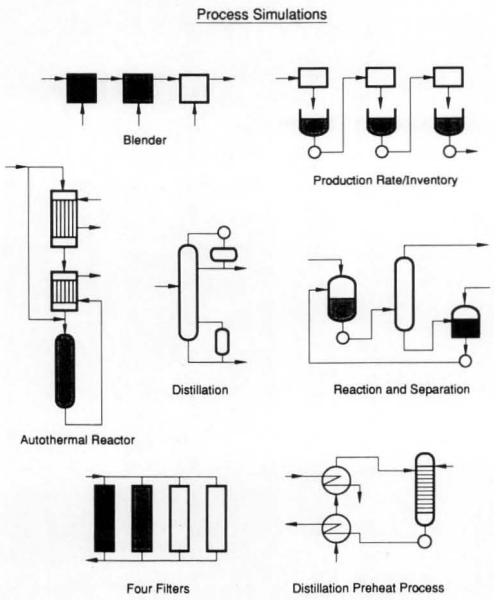

FIGURE 4. Simplified diagrams of simulated processes used for student exercises on multiloop control systems.

paraphernalia and multi-volume user's manuals of the ultimate industrial system. It also had to be coordinated with UC ONLINE in both its "real-world" and its simulation modes. That we have done. The student sees UC SIGNAL working as follows:

1. The Process Diagram

This diagram (constructed by the instructor as described shortly) is displayed on the screen when the user loads it from a file. This is accomplished by making a selection from a pop-up menu; the program then prompts for the name of the file. All measurement transducers and valves are included in these diagrams. The menu selection is accomplished with a mouse-driven screen cursor, and the name of the file is entered through keyboard input. When activity is directed to a process simulation, the names of all measured and manipulated variables are set identical to those used in the simulation module (a responsibility of the instructor); the program prohibits the student from changing them. Nominal values of process variables may also be read in. When working with "real-world" laboratory apparatus, the naming of the variables and the designation of an I/O channel number is at the discretion of the student and may be changed at any time. The instructor has the option of supplying or not supplying the parameters needed to convert transducer signals to engineering units (*e.g.*, millivolts to degrees Celsius). So that they know how to do this, our students have to work these out early in the semester; we supply the parameters in the later part of the semester.

2. Making Links

One item in a pop-up menu is named LINK, and its seletion with the mouse (or alternatively, with the keystroke L) enables the user to link any sensor with any actuator simply by first pointing to the sensor (the signal source) and then the actuator (the signal destination). A line representing the signal is immediately drawn on the screen without the user having to specify its route. The line is drawn to avoid all objects on the screen, with the exception that crossing of other signal paths and process streams is permitted. Using the same protocol, links can be made from an output of a control element (described shortly) to the input of another, or from any point on a signal to an input of an element or actuator. If the automatic signal routing is found inconvenient, the signal path can be rerouted. The signal can also be deleted and restored. Such "sketching" sets the skeleton of the loops. They have to be "fleshed out," however, with control elements before the structure can

be considered complete.

3. Inserting Control Elements

Any of a slate of control elements comprising a PID controller, a summer, a multiplier, a divider, high- and low-selection operators, a square root, and a lead-lag element can be selected from a pop-up menu and inserted at any point in any signal path. Linking among them can be accomplished in the manner just described. Elements can be exchanged with others if, for example, a multiplier was intended instead of a summer. They can be removed by elision and the signal restored automatically as it was before the element was inserted. And elements can be moved to any unoccupied location, with their signal links relocated automatically. It is also possible to place elements in "thin air" before links to them are made. Examples of the results of these operations are evident in the configuration shown in Figure 2.

The linking and inserting modes of the program are the workhorses of the system-configuration operation. The procedures used in these two modes are about as close as one can come to mimicking the pen strokes of an engineer as he sketches a system diagram on paper. And they are fast—just what we have been striving for. The procedures might even be considered as an advance over the pen-and-paper method because the signal paths are routed automatically. Most importantly, however, the visual relationship of control system to process is made clear—a relationship that can aid the designer in his system deliberations.

4. Setting Parameters and Interrogating Element Connectivity

A certain amount of "bookkeeping" has to be attended to before the control system can be considered operational. Parameters have to be set to convert measurement signals to engineering units, high and low limits need setting in both controller and system variables, and controller tuning parameters and initial valves of controller outputs have to be set. These tasks can be dispatched easily by entering numerical values in a pop-up parameter panel for every controller and system variable. To bring up the panel, the user simply picks the control element with the cursor. To help speed this data-input task, all high and low limits have been set to default values. The panels for the control elements have a field for accepting a name from the user. Usually, only controllers need to be specially named to aid the user in identifying the function of the controller. Any control elements not named by the user are given arbitrary names by the program upon request or upon output of the configuration to a file.

The assignment of function to the three input signals of each controller should be checked by the user before completing the system synthesis. Pop-up information panels (which are brought to the screen by pointing to a controller input signal), state whether that signal is assigned as a measured variable in the control algorithm or assigned as a setpoint or a guard variable. Provision is available for interchanging functions if need be.

5. Saving the Configuration

Complete information about the system (the graphical depiction, control element parameters, and linkages among the elements) can be saved to a file. That file can then be read back into UC SIGNAL again for the purpose of continuing work or to make modifications in the control system. A full-screen display of the system is recreated and a printed copy of the screen may be made at any time. The most important use of the file, however, is its use in communicating the control-system structure and content to UC ONLINE, the multiloop control program that executes the algorithms of the control elements placed in the system. All this can be done in a matter of seconds.

6. Features of the Instructor Mode

The program incorporates facilities to aid the instructor in constructing diagrams of the laboratory apparatus or simulated process. Such facilities are available only to the instructor. Process diagrams can be constructed rapidly through assembly of a set of prepared symbols and objects, using the same graphics operations employed in the student mode of operation. Actuators and sensors can be placed, named, and "fixed" into position so that they are unmodifiable by the student. These "diagram" files that the instructor creates are those that are presented to the student; the diagrams appear on the screen when the files are called up by UC SIGNAL. Figure 1 is such a diagram.

CLOSING COMMENTS

The thrust of our endeavors in developing UC SIGNAL and UC ONLINE is to open up opportunities for students to exercise their creative abilities in control-system synthesis. Without a facile and unfettered means of stating a proposed structure and without a means for demonstrating the workability of that structure, there would be little hope of achieving that goal. We now have those capabilities, and

through a carefully-crafted sequence of examples and encounters with various types of control-system substructures, one can expect to build in the students an expertise in control-system synthesis barely imagined just a few years ago. When we add to that the enthusiasm displayed by students in meeting such challenges, we are confident that we are getting better at this enterprise of engineering education.

REFERENCES

1. Foss, A.S., "UC ONLINE: Berkeley's Multiloop Computer Control Program," *Chem. Eng. Ed.*, **21**, 122 (1987) ❐

ChE **book review**

CHEMICAL REACTOR ANALYSIS AND DESIGN, *Second Edition*

by G.F. Froment and K.B. Bischoff
John Wiley & Sons, Inc., 1 Wiley Drive,
Somerset, NJ 08875-1271; 664 pages, $59.95 (1990)

Reviewed by
Edmund G. Seebauer
University of Illinois, Urbana

Overall, I found this book to be quite suitable for a graduate-level course in reactor analysis, but too advanced for undergraduates. I disagree with the authors' statement in the Preface to the First Edition that the book may be used in a less-extensive treatment as a text for undergraduates. The chapters are not set up to clearly distinguish elementary from advanced material and there are relatively few simple, straightforward examples of elementary concepts that many undergraduates need in order to grasp the material. The style of writing is quite formal and compact. The overall level of mathematics is also too advanced for most undergraduates. In principle, such students have seen the matrix algebra, vector notation, and differential equations which are presented in this book. However, I believe that most undergraduates have little facility with these concepts, so that the mathematics becomes an impediment rather than a tool for understanding. The problems at the end of each chapter contain too few drill problems for simple concepts that undergraduates need in their homework assignments.

However, the above statements should not be taken as criticisms; the style and content of the text and problems are quite suitable for graduate students. The treatment of important concepts is up-to-date and very well documented with literature references. Numerous summary paragraphs are included. While it might have been better to set these paragraphs off from the main body of the text, they are still quite useful. The table of symbols at the beginning of the book is also helpful. The detailed Table of Contents and the Author Index are execellent features, although the Subject Index is only average.

The treatment of chemical kinetics in Chapter 1 overreached itself in Example 1.4.4 and Section 1.6. The book does not pretend to be a text in physical chemistry (and rightly so). Hence, I found the treatment of transition state theory and the Lindemann mechanism to be so cursory as to be confusing. I would have mentioned these concepts in passing with only two or three sentences.

On the whole, however, it is a fine book. ❐

AN INTRODUCTION TO RHEOLOGY

by H.A. Barnes, J.F. Hutton, and K. Walters
Elsevier Science Publishers B.V., Amsterdam, The Netherlands; $100 hardbound, $65.75 paperback (1989)

Reviewed by
Charles Manke
Wayne State University

In the preface to *An Introduction to Rheology,* the authors acknowledge that rheology is a "difficult subject" and that those seeking an introduction are often discouraged by the mathematical complexity of standard textbooks. This new book aims to provide an understandable introduction to rheology for newcomers to the field, particularly those without strong backgrounds in mathematics. The mathematical content of the book is minimized by a strategic organization of the subject material that defers consideration of continuum mechanics and constitutive equations (where mathematical complexity is unavoidable) until the final chapter. However, certain mathematical treatments (such as the tensor representation of stresses) are regarded as essential, and they are used throughout the book. Overall, this approach is effective, and the authors succeed in presenting a well-balanced, understandable overview of rheology without oversimplification or lack of rigor.

The early chapters of the book focus on rheological phenomena, with individual chapters devoted to non-Newtonian viscosity, linear viscoelasticity, normal stresses, and extensional flow. Here the reader is introduced to the nature and origins of rheological

Continued on page 172.