Chemical Process Control Education and Practice

By B. Wayne Bequette and Babatunde A. Ogunnaike

Chemical process control textbooks and courses differ significantly from their electrical or mechanical-oriented brethren. It is our experience that colleagues in electrical engineering (EE) and mechanical engineering (ME) assume that we teach the same theory in our courses and merely have different application examples. The primary goals of this article are to i) emphasize the distinctly challenging characteristics of chemical processes, ii) present a typical process control curriculum, and iii) discuss how chemical process control courses can be revised to better meet the needs of a typical B.S.-level chemical engineer.

In addition to a review of material covered in a standard process control course, we discuss innovative approaches in process control education, including the use of case studies, distributed control systems in laboratories, identification and control simulation packages, and studio-based approaches combining lecture, simulation, and experiments in the same room. We also provide perspectives on needed developments in process control education.

Chemical Engineering Curricula

Chemical engineering curricula across the United States are relatively uniform for several reasons: departmental history and culture, Accreditation Board of Engineering and Technology (ABET) accreditation requirements, and the success of alumni in industry. Standard courses include material and energy balances, thermodynamics, equilibrium stage separations, transport phenomena, chemical reaction engineering, process dynamics and control, process design, and chemical engineering laboratory. Virtually every topic covered in these chemical engineering curricula assumes steady-state process operation—the sole exception is the process dynamics and control course, which must therefore accept the burden of introducing all topics associated with the dynamic behavior of process systems.

Characteristics of Chemical Processes

A major difference between process control and device control is the replicability of control system designs. For example, a disk drive manufacturer can perform a single advanced control system design for this device and use that controller in thousands of units. Each chemical process control system design project, on the other hand, tends to be unique. A styrene polymerization reactor in one manufacturing plant may have feedstocks, flow patterns, and product specifications that differ significantly from a similar reactor in another facility. Process operations management philosophy, plant control hardware and software, process engineering structure, sensor selection and maintenance, and the analytical laboratory vary substantially from plant to plant. These issues lead to virtually an entirely new control system development for each process, a factor that significantly influences process control practice and hence, indirectly, process control education.

The common characteristics that make chemical processes so challenging to control are noted in papers presented at most control research conferences and in countless research proposals. It is worth reviewing these problems here to understand if we are getting the major points across to our undergraduates. Chemical processes are usually high order, nonlinear, with multiple inputs and outputs; they have time delays, input constraints, and a limited number of measured states. The desired properties of a product stream are often not directly measured, so inferential control is important. Economic objectives are dominated by steady-state considerations. Large-scale processes are often energy integrated, causing a high degree of interaction between inputs and outputs of different process units. Specialty chemicals and pharmaceuticals are often produced in batches, frequently with a single vessel serving more than one function (heater, reactor, and separator, for example). The same temperature controller may be required to provide cooling under some conditions and heating under others. Often robustness, rather than nominal performance for any particular operating condition, becomes the prime consideration.

The proportional-integral-derivative (PID) controller is dominant in the chemical process industry and will remain so for many reasons. One is that lower-level loops, such as flow control, are adequately controlled by PID action. Also, no explicit process model is required for tuning the two or three controller parameters; many commercial PID controllers have autotuning algorithms. Cascade control is prevalent, since most higher level loops cascade a setpoint to a flow control loop. Feedforward and ratio control are used in well-studied unit operations. Distributed control systems (DCSs) are the norm, although the hardware/communications structure is significantly different from the systems of the late 1970s and 1980s. Most loops are sampled at a high frequency relative to the process dynamics, so continuous control system design procedures can easily be used.
Cascade control is worthy of further discussion, since the approach does not appear to be well known in other disciplines. An example of a double cascade control strategy to regulate temperature of a chemical reactor is shown in Fig. 1; the corresponding block diagram is shown in Fig. 2. The dominate time constant for the flow control loop is a few seconds, the jacket temperature loop is a few minutes, while the reactor temperature may be several minutes to several hours (particularly for a polymerization reactor). Notice that each control loop rejects different disturbances. The flow control loop rejects coolant header pressure disturbances and compensates for valve nonlinearities. The jacket temperature control loop rejects coolant header temperature disturbances. The reactor temperature controller rejects reactor feed, temperature, and concentration disturbances and compensates for changes in the rate of heat transfer due to fouling, etc. This approach has many of the benefits of a state feedback strategy used in other disciplines, without sensitivity to model uncertainty.

The most commonly used advanced control scheme is model predictive control (MPC). The basic idea behind MPC is illustrated for a single-input, single-output process in Fig. 3. Here, an open-loop optimal control problem is solved at time step $k$. The least-squares objective function to be minimized is based on the residuals between the model predictions and the desired setpoint profile over a horizon of $P$ time steps. The decision variables are the next $M$ control moves; note that the control moves can be constrained. Only the first control move is actually implemented and the next process measurement is obtained. The model is updated and a new constrained optimization problem is solved at time step $k+1$. Multivariable systems with constraints and time delays are handled naturally by MPC. MPC has been particularly successful in the petroleum refining industry where large-scale, interacting, constrained systems are the norm. Time constants and sample times are large, so computation time to solve large-scale constrained systems is not an issue. When linear models and quadratic objective functions are used, the optimization problem results in a quadratic program (QP), there are a number of robust QP codes available. For a tutorial overview of MPC, see Rawlings [1]. Again, we should stress that it is common that flow rates are the manipulated inputs used by MPC strate-
gies. The manipulated flow rates are set points to flow controllers, which remain PID.

**Current Status of the Chemical Process Dynamics and Control Course**

Most chemical engineering departments in the United States offer a single course in dynamics and control, which is most often taught during the first semester of the senior year, although an increasing number of schools are teaching this course during the junior year [2].

**Topics**

Table 1 summarizes topics covered in a typical dynamics and control course. Contrast these with topics taught in EE and ME systems and control courses [3], shown in Table 2. It is particularly striking that state-variable techniques, signal-flow graphs, and Nichols charts are rarely studied in chemical engineering (ChE) courses yet widely studied in EE and ME.

A few critical topics distinguish ChE from EE and ME systems and control courses and books. Dynamic models are usually not encountered in other chemical engineering courses; thus, in process control courses, significant time is spent on the development and analysis of dynamic chemical process models. Almost all chemical process models based on fundamental material and energy balances are nonlinear. Even simple mixing problems are bilinear, since a manipulated input (flow rate) often multiplies a state (concentration or temperature). More complex chemical reaction models include the Arrhenius rate expression, where reaction rate is an exponential function of the reactor temperature (students learn in reaction engineering courses that this can result in multiple steady-state behavior). It is therefore important for chemical engineers to learn linearization before they begin to analyze dynamic behavior. Contrast this with the numerous inherently linear circuit and mechanical systems; EE and ME students can begin to learn linear dynamic behavior before worrying about understanding linearization.

State feedback techniques are not commonly applied to chemical processes since few states are measured. Much of the focus is on classical feedback using continuous PID control. There has been a trend to incorporate more model-based techniques, primarily internal model control (IMC) and MPC.

A number of process dynamics and control textbooks are currently available (Table 3). It should be noted, however, that most of the basic topics covered do not differ substantially from Coughanowr and Koppel [4], the first widely used textbook. Stephanopoulos [5] was the first to present a detailed treatment of digital control and to discuss plantwide control.
Seborg et al. [6] provide the first treatment of dynamic matrix control and model algorithmic control, two model predictive control algorithms. Luyben [7] has a strong focus on modeling and simulation and realistic physical examples. Marlin [8] does a good job of considering the integration of process design and control; it also has a MATLAB workbook available to instructors. The text by Ogunnaike and Ray [9] is almost encyclopedic in its coverage of process control techniques. Luyben and Luyben [10] include a strong section on plantwide control. A forthcoming book by Bequette [11] focuses on model-based control and contains MATLAB-based modules that treat specific unit operation control problems in depth. In contrast to these textbooks, which generally analyze and synthesize controllers in the Laplace or frequency domains, the text by Svrcek et al. [12] takes a time domain approach. Case study “workshops,” using chemical process simulation software, are used to reinforce basic concepts.

Deshpande [13] has suggested that more attention should be paid to statistical process/quality control (SPC/SQC). He presents a course that adds several topics to the standard course; it is not clear what topics should be omitted to fit this expanded version into the same number of course hours.

**Simulation**

Most control courses make use of a simulation package such as MATLAB. Bequette [14] presents a two-course sequence in dynamics and control that makes use of the MATLAB simulation environment for homework assignments and special projects. Rensselaer has since moved to a single, four-credit course covering dynamics and control. Bequette et al. [15] provide details of a case study project in multivariable control. Students, working in teams, select a unit operation (from a list of five) to study for the last third of the semester. The project begins with a literature search, followed by process identification (the “process” is a SIMULINK masked block diagram) and single-input, single-output (SISO) control loop design. The groups then study multiple SISO loops and decoupling, write a final report, and give an oral presentation. Doyle et al. [16], [17] present an integrated MATLAB-based set of modules with several low-order linear systems and higher-order processes such as furnaces and biochemical reactors. MATLAB-based modules focusing on process dynamics studies are presented in Bequette [18].

Cooper [19], [20] at the University of Connecticut has developed a PC-based package called Control Station that simulates the dynamic behavior of several common chemical processes. Realistic problems such as noisy measurements, unmeasured and measured disturbances, and manipulated variable saturation are included. The package can also be used to develop models from experimental data.

<table>
<thead>
<tr>
<th>Topic</th>
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<tr>
<td>Process Dynamics and Modeling</td>
<td>28.1</td>
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<tr>
<td>Feedback Control and Tuning</td>
<td>22.1</td>
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<tr>
<td>Stability and Frequency Response Analysis</td>
<td>14.3</td>
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<td>Computer Simulation</td>
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<td>Advanced Control Techniques</td>
<td>8.4</td>
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<td>Control System Hardware</td>
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<td>Computer Control Systems</td>
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<th>Topic</th>
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<td>Root-locus techniques</td>
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<td>Routh-Hurwitz stability test</td>
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<td>State-variable techniques</td>
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<td>Signal flow graphs</td>
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<td>Sensitivity analysis</td>
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<td>56</td>
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<tr>
<td>Nichols charts</td>
<td>47</td>
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**Table 1. Common Chemical Process Dynamics and Control Course Topics [2].**

**Table 2. Top 8 Topics Covered in EE and ME Undergraduate Control Courses [3].**

**Table 3. Process Control Textbooks.**

- Bequette [11]
- Coughanowr [38]
- Coughanowr and Koppel [4]
- Erickson and Hedrick [39]
- Luyben [7]
- Luyben and Luyben [10]
- Marlin [8]
- Ogunnaike and Ray [9]
- Riggs [40]
- Seborg, Edgar, and Mellichamp [6]
- Smith and Corripio [41]
- Stephanopoulos [5]
- Svrcek, Mahoney, and Young [12]
Laboratory Experiments

Some departments have control laboratories that are associated with the control course, whereas others have control experiments that are part of the unit operations laboratory course, usually taken in the senior year. The majority of control laboratories use PC-based data acquisition and control software where a single PC is interfaced to a single experiment. Braatz and Johnson [21] at the University of Illinois use the Hewlett-Packard Visual Engineering Environment to provide a graphical operator interface for bench-scale experiments. Holt and Pick [22] at the University of Washington present a two-tank experiment controlled by a MacIntosh and Workbench software. Their philosophy is to use the same experimental apparatus throughout the quarter; students conduct initial experiments on sensor calibration, design single-loop controllers, and finish the quarter with multiple single-loop controller design and implementation.

There are some departments, however, where industrial DCS-based systems are used. Rivera et al. [23] at Arizona State University use a Honeywell TDC 3000-based system to control 11 of 12 experiments in a senior unit operations laboratory. Most of the experiments are bench scale. Sklar et al. [24] at the University of Utah use an Opto22 DCS to monitor and control seven laboratory experiments; eight more are planned. Pintar et al. [25] at Michigan Tech have developed a TDC 3000-based system to control a 30-gal jacketed polymerization batch reactor (producing polydimethylsiloxane) and a 30-ft-high distillation column, neither of which is commonly available in academic settings. Students receive extensive safety training for this laboratory.

Experimental equipment can be expensive and not cost effective if only operated a few days each year. Henry [26] has developed a Web-based virtual laboratory where students from across the world can perform remote dynamics and control studies on experiments at the University of Tennessee-Chattanooga (http://chem. engr.utc.edu/Webres/Stations/controls lab.html).

Industrial Views on Undergraduate Education

Several papers authored by industrial practitioners make suggestions on how undergraduate education can be changed to meet the needs of practicing engineers. Downs and Doss [27] feel that the control educational paradigm has been to i) start with a purely mathematical description (abstraction), ii) develop, analyze, and evaluate theoretical descriptions, and iii) apply the theory to specific abstractions (e.g., “For this transfer function design a controller...”). They contrast this with the case study paradigm used in the medical, legal, and business professions where instructors: i) present a single illustrative case, ii) abstract lessons from the specific to the general, and iii) iterate i) and ii) such that there is a gradual buildup of an overall abstract knowledge base supported by hundreds of case studies.

Ramaker et al. [28] feel that control students should be taught using concepts that fit with the rest of the chemical engineering education. Since the rest of the curriculum emphasizes time domain ideas such as flow rates, residence times, and rate constants, frequency domain concepts should not be a primary focus. Contrast this with electrical engineering where many concepts are taught in the frequency domain.

In fact, there is as yet no true consensus perspective from industry. The strictly theoretical approach is clearly inadequate because it fails to confront students with enough of the real-life issues encountered in practice. By the same token, the strict case-study approach is inadequate: given that there is a limitless number of actual chemical processes, no single case study can provide all the requisite ingredients for teaching the concepts necessary to solve problems other than those within the scope explicitly covered by such an isolated case study. A balanced approach in which the basic principles are taught first and then illustrated with practical case studies is probably more productive in the long run.

Goals for Undergraduate Process Dynamics and Control Education

Notice that there is not enough overlap between the perceived challenges in the control of chemical processes and the actual topics typically covered in an undergraduate course.

Since there is a limited amount of time to cover the many important concepts in dynamics and control, it is imperative that many of these concepts be introduced in other courses. Laplace transforms have been taught in the differential equations courses for many years; a primary problem is that students often do not appreciate the connection between the nth-order linear differential equations and physical reality. Too much time is often spent reviewing matrix
algebra concepts in the dynamics and control course. Again, the linear algebra course tends to be too abstract, with little motivation for how eigenvalues/eigenvectors can be used to understand engineering problems. Dynamic models should be introduced in the introductory material and energy balances course; Felder and Rousseau [29], for example, include a chapter on dynamic models in their popular textbook.

There is certainly a strong argument for considering process systems engineering throughout the curriculum. Every chemical engineering course should have some design/operation/control components; all courses should still have important fundamental science in their content, but these must be accompanied by application examples that will motivate the students to learn the fundamentals and applications.

**A Look Back at a Look Forward**

At the dawn of a new millennium, it is appropriate to review ideas presented a decade ago by Edgar [30], who suggested curricula for a course on dynamics and control in 2000; his suggested topics are presented in Table 4. One pie-in-the-sky concept that has not come to pass is the common use of nonlinear programming techniques; some courses do cover MPC, but usually focus on the unconstrained form, which has an analytical solution for linear process models. Also, there continues to be a focus on continuous-time rather than discrete-time design and analysis. An important topic notably missing from the 2000 course is statistical process/quality control.

**A Desired Course in Chemical Process Dynamics and Control**

During the past decade, there has been a major impetus in engineering education to change from a teacher-centered lecture environment to a student-centered learning environment. This has generally required instructors to remove some course content, sacrificing breadth for depth. Since students tend to take home only a few major concepts from a course, we feel it is more important for them to learn critical analysis skills rather than to solve a smattering of problems in a large number of areas. A particular type of student-based learning is the studio approach. In studio teaching, the instructor provides motivating mini-lectures and poses problems to be discussed and solved in class. The instructor serves as the “guide on the side” rather than the “sage on the stage.” Some perceived problems with this approach, when computer-based tools are used for problem solving, is that students are often learning how to use software rather than how to formulate and solve engineering problems.

The particular view at Rensselaer is to combine the most positive attributes of lectures, simulation-based laboratories, and experimental laboratories into a single course [31]. Simulation-based assignments have become more common and are used to illustrate problems that cannot be easily studied using classical pen-and-paper analytical solutions. Although simulation-based assignments provide much insight into practical control system issues, nothing can take the place of hands-on experiments. To this end, we have developed a control studio that combines lectures, simulations, and experiments in a single classroom. We have constructed a classroom facility that seats 40 students and includes 20 computer-based simulation and control workstations. The students face the front of the studio dur-

![Figure 4. The Rensselaer prototype chemical process control experiment. Fresh feedwater, regulated with a control valve, flows into the vessel containing an electric heater (upper left). Concentrated salt water, which is regulated with a control valve, then mixes with the heated feedwater in a small mixing tank that contains a temperature probe. The effluent from this tank discharges through a conductivity sensor into the sink.](image)
ing lecture and discussion periods and swivel in their chairs to perform simulations and conduct experiments on the countertops behind them. During the problem-solving periods, the instructor and teaching assistant move around the room answering questions and generating discussion. Most of the problems have been solved in two-person groups; however, the space could handle a group size of three. Although it is conceivable that 20 copies of a single experiment could be used so that all groups are working on the same problem, this is not economically attractive. It is more attractive to have roughly five copies of an experiment; groups working with an experiment during one period may be doing simulations or a detailed design project during the next period.

A prototype chemical process control experiment, shown in Fig. 4, mimics the behavior of a typical chemical process. Fresh feedwater, regulated with a control valve, flows into a vessel containing an electric heater. A concentrated salt solution from a reservoir then mixes with the heated feedwater in a mixing tank that contains a temperature probe. The outlet from the tank discharges through a conductivity sensor into a sink. The objective of the experiment is to regulate three measured process variables (level, temperature, and conductivity) at desired setpoint values by manipulating three input variables (freshwater flow rate, concentrated salt solution flow rate, and heater power) via feedback control. The experimental apparatus is benchtop scale (with a “footprint” of roughly 3 ft²), so that it can be used in the studio classroom. The experiment was designed to have time constants that are roughly 20-30 s; the time scale is slow enough for students to observe the physical changes, yet fast enough for a number of experiments to be conducted during an interactive session. National Instruments hardware and software (LabVIEW) is used for data acquisition and control. The control interface shown in Fig. 5 is intuitive, with a simple process and instrumentation diagram that closely matches the experimental apparatus.

We currently use two-hour sessions, twice a week, for the studio; a third session is used for recitation and provides time for students to “catch up” on assignments. Shorter periods would not allow enough time to set up and perform experiments, whereas significantly longer periods would be draining for students and instructors alike.

Graduate Education

The focus of this article has been on undergraduate education. Since most chemical engineering departments have a single faculty member with expertise in systems and control, rarely is more than one graduate-level process control course taught on a frequent basis. The available selection of graduate-level process control textbooks is limited [32]-[34]. Graduate students conducting research in process control generally take several systems and control theory courses in electrical engineering departments. Special topics in chemical process control are normally covered in course notes and instructor handouts. MPC is probably the most covered special topics process control course; several MPC textbooks/monographs are currently in preparation. Nonlinear control is probably the next most widely taught special topics course. A monograph on nonlinear process control has been published [35] but does not appear to be widely used in these courses. As plantwide control begins to receive more attention, the monograph by Luyben et al. [36] will probably be the text of choice.

It is widely recognized that graduate students need more practical control experience, so there is a move to develop experiments for graduate control courses. An example from a graduate-level multidisciplinary control laboratory at the University of Delaware is presented by Gatzke et al. [37].

Summary

The primary purpose of this article is to provide a summary of chemical process control education and practice for our colleagues in other engineering disciplines. We have presented a typical process control curriculum, outlined some of the distinctly challenging characteristics of chemical processes, and discussed recent and ongoing developments in process control education. We consider control education to be an area where “continuous improvement” is important and look forward to discussions based on this article and education sessions at future control conferences.

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References


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