PROCESS CONTROL EDUCATION IN THE YEAR 2000

A Round Table Discussion

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THIS AUTHOR RECENTLY presented a paper on process control education at a joint India-U.S. symposium in Bangalore, India [1]. The paper [2] reviewed the current practices and philosophy of teaching undergraduate process control in a typical chemical engineering department and presented an outline for a course to be taught in the year 2000. This future course would cover the forecasted advances in hardware and software which should take place in the next ten to fifteen years.

A main difficulty with the one-semester process control course at most schools is that its starting point is still the same as it was when the landmark textbook by Coughanowr and Koppel [3] was first published in 1965. In order to incorporate all the advances in control engineering that have taken place in the past twenty-five years (as well as the projected developments) considerable streamlining of the curriculum material must be carried out. The problem faced by most educators is that we tend to adjust courses in a slow feedback mode. We do not adapt a course in a feedforward fashion so that it will match the technology encountered by BS graduates in a modern chemical plant.

In an effort to promote some thought and discussion within the process control community and to begin making curriculum changes now, an outline of a future course (discussed later in this paper) was circulated to a cross-section of educators and industrial practitioners for their comments, criticisms, and suggestions. Many of the responses were quite detailed and most interesting, and edited comments are presented in the Appendix to this paper. There is a surprising amount of agreement on the directions in which the field is moving, although there is no clear consensus on how a one-semester course can accomplish the stated objectives. Perhaps a two-semester sequence (such as is practiced in many schools abroad) is the only answer.

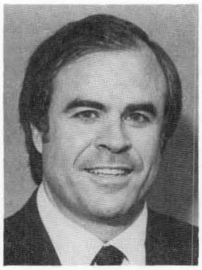

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TABLE 1
Course Outline for Process Control (*ca.* 1988)

1. Introduct. concepts: feedback *vs.* feedforward control (1 week)
2. Mathematical modeling of physical systems (1 week)
3. Linear system analysis: Laplace transforms (2 weeks)
4. Response characteristics of typical process systems (1 week)
5. Controller hardware, instrumentation (1 week)
6. Closed-loop analysis, stability calculations (1 week)
7. Tuning of PID controllers (2 weeks)
8. Frequency response analysis (1-2 weeks)
9. Advanced control methods: feedforward, cascade, multivariable, adaptive, supervisory, *etc* (3-4 weeks)
10. Plant control strategies, case studies (1 week)
11. Miscellaneous topics

The above outline excludes time spent in an associated process control laboratory.

GOALS OF AN UNDERGRADUATE PROCESS CONTROL COURSE (1988)

A one-semester or one-quarter undergraduate process control course is required in virtually all US departments of chemical engineering. In some cases a two-quarter or, more rarely, a two-semester course is taught. The content of a typical undergraduate process control course is not intended to train process control specialists. Rather it presents the key concepts in dynamics and control and attempts to inculcate in BS engineers an understanding of transient operations and the influence of feedback control on responses.

A typical course has the following learning objectives:

- *Understanding the difference between dynamic and steady state behavior – courses in chemical engineering generally deal with steady state analysis only. This fact sets apart the subject matter in process control from other courses in the curriculum. Mathematical modeling is a key ingredient.*
- *Becoming proficient in analysis of dynamic systems – the principal tool employed in Laplace transforms. As long as the course focus is on linear continuous systems, Laplace transforms will always be the starting point, unless this is covered in a prior course in mathematics. The amount of emphasis on Laplace transform operations is an important issue, as discussed below.*
- *Learning the effect of feedback control and several industrially-accepted methods of tuning PID controllers – this leads to the issues of stability and performance in designing feedback controllers. Computer simulation with interactive graphics is a key pedagogical tool.*
- *Appreciating the benefits of advanced methods such as feedforward and cascade control – students should know under what conditions various methods should be implemented.*
- *Exposure to modern instrumentation and controller hardware as practiced in industry – in particular, a digital control system interfaced to an actual process. A laboratory experience should be included in the control course or as part of a unit operations laboratory.*

Table 1 shows the typical course content for a 15-week process control course based on 1980s textbooks such as Stephanopoulos [4], Smith and Corripio [5], or the new book by Seborg, Edgar, and Mellichamp [6].

There is wide disagreement on the amount of time that should be dedicated to mathematical modeling, since every additional hour spent there must be taken away from other material. Exemplary systems can be studied, such as the stirred tank heater which is described by a first-order linear differential equation. However, systems of industrial relevance are quite complex, and developing models for these systems in a few weeks of a process control course is clearly beyond the capabilities (from a fundamental point of view) of a typical undergraduate student. Nevertheless, such models can be presented to the student by employing simulators with rich graphics capabilities. The objective of such a simulator is to give the student a "feel" for dynamic behavior. However, it is unrealistic to expect the student to become even marginally competent in simulation or associated numerical analysis issues in this course.

Laplace transforms are the basic mathematical tool in procss control, and the teaching of this subject (along with frequency response) has historically been viewed as a major part of a process control course. However, given the emergence of mainframe and personal computer software for linear systems analysis and simulation, does the current heavy emphasis on Laplace transform manipulations need to be reevaluated? The early dependence on Laplace transforms arose out of necessity because computational and graphical tools were not available. Rigorous analysis was necessary to obtain transient responses. As a tool for complex systems, Laplace transform analysis to obtain time-domain responses is of marginal utility, especially when time delays exist in the process. The key to reducing the current course effort on linear systems analysis is the good interactive software which is available today [1]. It also would be helpful to modernize and focus the differential equation course which is taught by our colleagues in the mathematics department.

The basic ideas in stability and PID controller tuning are important, but interactive software can be employed to solve realistic problems after a few tutorial examples. Root locus should only be briefly mentioned.

Controller hardware and instrumentation is a subject which requires continual updating as new products are introduced. While there is a lot of material here, most of it is descriptive in nature and tends to be vendor-specific. It should be mandatory that some background on the digital version of the PID controller be provided here since all controllers sold today are digital units (that appear to be analog). Programmed logic controllers (PLC) should also be covered.

The basic ideas in stability and PID controller tuning are important, but interactive software can be employed to solve realistic problems after a few tutorial examples. Root locus should only be briefly mentioned.

There are many ways to tune a PID controller [6]. Methods based on stability considerations alone are generally not satisfactory; performance-based methods are both stable and predictable with respect to the design criteria. For simple systems, most tuning methods give approximately the same results. The effect on model errors should also be addressed, leading to a robust PID controller. In controller design the quality of the results depends directly on the level of computational effort. The Ziegler-Nichols algebraic correlations based on the process reaction curve and the quarter-decay ratio give inconsistent performance. Improved performance can be achieved by frequency response. While application of this technique can be tedious, especially when undertaken manually, interactive computer graphics permits the design of a PID controller to be completed very quickly. Unfortunately, many engineers who are responsible for controller tuning were subjected to the manual trial and error approach while they were students and have never since looked at this option. The fact that frequency response is rarely used in industry needs to be addressed (and corrected) by the educational sector.

The understanding of modern control systems provided by vendors or design firms requires consideration of a number of advanced control strategies. In the early 1970*s*, there were only a handful of plants using feedforward control. This algorithm is now considered to be the standard approach when combined with feedback control. Just as significant, cascade control is routinely used in computer control systems. Multivariable and adaptive control are of lesser importance, although industrial activity in these areas is growing rapidly. Industry is especially interested in self-tuning (adaptive) controllers because of reduced manpower requirements and improved performance with a negligible cost difference.

Plant control strategy is a topic properly emphasized throughout the text by Stephanopoulos [4]. While it may be arguable that the average undergraduate student is not intellectually mature enough to absorb this type of material on top of everything else, case studies which analyze a group of interconnected unit operations rather than a single process unit have merit as the "capstone" component of a course in process control. Safety issues also should be covered here.

Table 1 has omitted many specific topics that could be covered in an up-to-date control course; see Table 2. Many of these topics will increase in importance in the future.

PROCESS CONTROL IN THE YEAR 2000

What will the state of affairs be in the year 2000? While most educators believe the undergraduate students of that era will be more facile with the use of computers, it is unlikely that there will be a quantum jump in the mathematical preparation of those students. So the starting point of a typical course will be about the same. However, the industrial environment where process control is carried out will probably be quite different than it is today. Because of greater integration of the plant equipment, tighter quality specification, and more emphasis on maximum profitability while maintaining safe operating conditions, the importance of process control will be increased. Very sophisticated computer-based tools will be at the disposal of plant personnel, who will at least need to understand the functional logic of such devices. Controllers will be self-tuning, operating conditions will be optimized frequently, total plant control will be implemented using a hierarchical (distributed) multivariable strategy, and expert systems will help the plant engineer make intelligent decisions (those he or she can be trusted to make). Plant data will be analyzed continuously, reconciled using material and energy balances with optimization, and unmeasured variables will be reconstructed using parameter estimation techniques.

How much emphasis needs to be placed on advanced techniques in the year 2000 course? Should we abandon analog (continuous) analysis methods in favor of digital ones such as z-transforms? What about the PID controller? Will it be replaced by a more general approach based on nonlinear programming? The answers to these questions are complicated by the fact that advancements in undergraduate education do not really cause a new industrial environment. There is probably much more influence at the graduate level. The second problem is that there is a great lack of uniformity in the modernization of chemical plants with respect to process control.

By the year 2000, the analog systems currently in use will have been replaced by digital systems. There will probably be sufficient computing capability available in each process plant (via distributed control) to implement any or all advanced techniques. There will still be single-loop panel-based controllers and control systems utilizing personal computers; while these can communicate with higher level computers, they will employ many different algorithms and functions than those offered in the standard PID controller today. So this may be the time when the standard undergraduate control course can be largely converted to digital control. Laplace transforms could be eschewed in favor of discrete time analysis (difference equations) and z-transforms.

Table 3 shows a 15-week lecture course for the

TABLE 2
Additional Topics for Undergraduate Process Control

- Alarms
- Computer control systems, data acquisition
- Predictive control
- Simulation
- Distributed control
- Unit operations control applications
- Batch sequence control
- Process control languages
- Statistical process control
- Process control data base management
- Real-time computing, architecture
- Expert systems, AI
- Digital control algorithms
- State space analysis
- Supervisory control
- Model identification

year 2000 and indicates the emphasis of various topics. The selection of topics can be justifiably criticized because it presupposes a reasonable level of training in fields such as optimization. It also demands that Laplace transforms and linear dynamic systems be (appropriately) taught in the mathematics department. However, fifteen years from now we could use nonlinear programming tools in the same way as we employ numerical analysis for simulation today. The student does not need a deep understanding of the numerical details involved in order to have confidence in the answers. Even today linear and nonlinear programming tools have matured to the point that they are used routinely in commercial operations and serve as the basis for management and operating decisions [7]. Optimization can also provide a unified approach for model identification and parameter estimation.

The course in Table 3 would emphasize developing familiarity with the techniques of process control, with a distinct unit operations flavor. A one-semester course would be insufficient to train specialists in process control, more so than it is in 1988. However, the ability of an engineer to creatively solve process control problems can be enhanced by continuing education and experience.

TABLE 3
Course Outline for Process Control (*ca.* 2000)

Topics	Comments
Dynamic Simulation (2 weeks)	*Concept of time constants for various physical systems, nonlinear behavior, commercial simulation packages*
Response characteristics (1 week)	*First, second, and higher order; unusual response characteristics (with examples)*
Development of discrete-time models (1 week)	*Fitting of discrete-time equations to data, use of convolution models*
Analysis of discrete-time systems (2 weeks)	*z-transforms, transfer functions, stability analysis*
Conventional and predictive controller structures (2 weeks)	*Conventional digital feedback vs. predictive control, supervisory control, cascade implementation of control trajectories*
Optimization methods for controller design (2 weeks)	*Optimal tuning of PID controllers, nonlinear programming formulation of design problem (e.g., dynamic matrix control or DMC), constraint handling*
Tuning of controllers/ robustness (1 week)	*Effect of tuning parameters for PID/predictive controllers, treatment of model errors*
Feedforward, adaptive, and multivariable control (2 weeks)	*Extension of optimization methods to cover disturbance rejection, model parameter changes, and multivariable interactions*
Digital hardware/implementation (1 week)	*Equipment features and configurations, sampling, filtering*
Expert systems (1 week)	*Structure and purpose of expert systems, alarm analysis, selectors*

NOTE: Laboratory experiments employing a modern digital control system are recommended to supplement the lectures described above.

Obviously the content of the undergraduate process control will not exhibit a step change near the year 2000 but will evolve more or less continuously. This will require the interim development of educational materials to supplement existing courses. Probably the biggest discontinuity will arise in the conversion from continous-time analysis (*e.g.*, Laplace transforms) to discrete-time, but this transition may never occur completely.

SUMMARY

Process control is a rapidly changing field, and its high technology nature demands continual updating of process control courses and laboratories. Perhaps the major issue to be addressed for the future is the role of continuous tiime analysis (*vs.* discrete-time) and increased use of simulation. A larger role for optimization in process modeling and controller design is envisioned.

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APPENDIX

Manfred Morari: Caltech

If you consider Laplace transforms simply as a tool for solving differential equations, then this aspect of Laplace transforms is obviously obsolete, and the use of Laplace transforms for obtaining system responses should be totally de-emphasized in the future curriculum. I, however, look at Laplace transforms and frequency response analysis more as a means of understanding the issues of stability, performance and robustness. There is simply no replacement in sight which conveys these issues with the same clarity.

a. *The effect of a time delay variation, for example, on the stability and performance of a control system can be easily explained and nicely understood from a Nyquist curve analysis. Any other method would involve only trial and error via simulation and would not transmit the same degree of insight.*

b. *With the proper training, an undergraduate can learn to look at a Bode plot (obviously generated by CAD software) and determine from one curve the speed of response, the likelihood of overshoot,* *steady state offset, the behavior of the system for a range of different disturbances, the possible sensitivity of the closed loop system to modeling errors, if non-minimum phase characteristics are present, etc. To obtain the same information and insight from either an analysis of difference equations or extensive simulations would be essentially impossible, or, to say the least, rather involved.*

"Will the PID controller be replaced by a more general approach based on nonlinear programming?" Largely not. The one important issue absent from your paper is modeling. The PID controller provides reasonably good control with a minimum of modeling effort. The information required to set up a nonlinear program for online control is much larger and in most cases the effort is not justifiable. This is also the reason why fewer model predictive control schemes have been implemented than the public has been led to believe.

Irv Rinard: CUNY

One concern is that process control has traditionally been taught from the bottom up. Now that is okay if we are training our students to be process control engineers. But if the plant control engineers are going to be chemical engineers who occasionally have to worry about process control along with a lot of other things, bottom up is probably not appropriate. They spend a semester getting to the point where they can analyze and design a SISO feedback controller, then they go out into a chemical plant only to find out that PID controller tuning is not the plant's critical control problem.

Along the lines of what you have suggested, perhaps there should be two undergraduate control courses: one an overview course which everyone would take, and a second course for those who intend to go into the systems engineering side of the business.

Another concern is that the focus of process control has been too narrow. Algorithms and their implementation have received most of the attention. Students go forth only to learn that measurements can be biased, or noisy, or fail altogether; that control valves stick; and that other critical items are either messed up or maxed out. Tuning a loop is more than just determining P, I, & D: it is also zeroing and spanning, fixing and adjusting, and sometimes even rewiring. Ninety percent of a proper computer control algorithm is data checking. While the topics of data reconciliation and fault diagnosis are on your agenda for the year 2000, they belong properly and prominently in the very first undergraduate course.

Along the same lines, students go forth thinking that the regulatory control system is it. They are almost totally unaware that the most important control system in the plant is not the regulatory control system, but the safety system. The former affects the size of your paycheck: the latter, whether or not you'll be around to collect it. Only Rijnsdorp has given this subject any coverage in a control textbook, at least as far as I can recall offhand.

What I would like to see is a revision of the entire curriculum to make it more model-based. Students should connect the basic idea of dynamic simulation to the solution of differential equations early on. Then, in the various courses, the appropriate models would be developed as a pedagogical tool. For instance, in thermodynamics, instead of learning about flash calculations in the abstract, the students could develop a dynamic model of a flash drum: in unit operations, dynamic models of heat exchangers and distillation columns. Then, when they get to the process control course, they already have the basic background in process modeling. I have found in teaching process control that modeling is what the students are weakest in. Emphasizing it throughout the curriculum might help. Perhaps this is an issue that CACHE should take up.

Jim Doss: Tennessee Eastman

In order to streamline the curriculum, a first step would be to put Laplace transforms into the mathematics courses. However, students tend not to retain the mathematical theory but to remember the experiences from control laboratory experiments and simulations. It is also important to emphasize the use of computation, especially with computer graphics. Students need to learn more about modeling and identification of process models. More digital control needs to be presented, and a parallel presentation of s and z transforms (such as in Saucedo and Schiring's textbook) might be necessary in the future. However, other digital devices such as PLCs and their use in interlocks are important, combined with discussion on alarms and process safety. Finally, students need to understand the concept of total plant control.

Wayne Bequette: Rensselaer Polytechnic Inst.

It is interesting that ChEs handle process control so well, despite the fact that we are trained (at the BS level, where 90% of the control engineers come from) on black box or linear system models. Our knowledge of "real" processes comes from our background in steady state modeling and design. Rarely in a typical BS curriculum are we teaching students using complex, nonlinear dynamic models. Our ideas, when we get into industry, about what effect certain manipulated variables have on certain output variables are based solely on our steady state background. I guess that one of the most important experience that an undergraduate control student can have is controlling laboratory equipment. A good dynamic process simulator can provide almost as good of an educational experience.

Sometimes it is amazing how well ChEs control processes in the real world, with such a poor theoretical background. It is well known, of course, that it takes a year or two of experience before a BS candidate can make a real contribution–but this is true of most industrial positions, not just process control engineering. In addition, most problems will be solved by the simplest method available, so the lack of theory is not a major hindrance.

I believe that for the vast majority of control loops, there will be no issue of digital vs. analog control. The lowest level of control (constituting > 80% of the loops) will continue to be a simple PI flow controller. The sampling rate is high at this level, so there is not a vast difference between digital and analog control. The main advantage of digital at this level is the ease of maintenance issue. That will be the main advantage of most loops for a period of time, because, if a particular control strategy is ineffective, digital technology allows a quick retrofit.

Brad Holt: University of Washington

Some of the key questions really must be dealt with. Should we be teaching continuous or discrete control theory? Can we teach the course using discrete theory completely and yet convey to the students the feel for dynamics and modeling that we do with continuous theory? How does modeling fit into such a course? Do we teach them difference equations or discrete approximations to ordinary differential equations? There simply is not time in such a course to teach both continuous and discrete theory, but almost all of the discrete texts that I have seen really assume a continuous background. Although I feel that teaching the course from the discrete standpoint would be very valuable, I haven't figured out how to do it and convey all of the ideas and information that we do now.

One important area which I feel that you could have said more is in how to actually design controllers. Most of the control books present P, PI, and PID as "the" controllers. You select one of these and then follow some rules to tune it. The books do not do a good job of suggesting when they will work well, when they don't and why there are problems. This year I taught the seniors an IMC based control philosophy as the first step. We started with feedforward controllers and how to design them, progressed to IMC as a technique to handle disturbances and uncertainty, and finally introduced the standard control configuration as the normal implementation method. This led to PI and PID controllers, how to tune them, and when they are likely to work. The students really feel that they know how to "design" controllers. They understand the role of uncertainty, the importance of models, and why systems with non-minimum phase elements are difficult to control. Although I will do some things differently next year, the experiment worked rwell.

Daniel Rivera: Shell Development

The course should begin by reflecting on fundamental system properties that establish chemical process control as a field in its own right. The effect of deadtime, inverse response, constraints, uncertainty, and operating requirements on achievable closed-loop performance should be emphasized. Discussing these issues can be done at the beginning of the course because these represent inherent limitations independent of control design. All of the course material should revolve upon technologies to meet these requirements.

The benefits of Laplace and frequency--domain methods should not be rejected because of implementation considerations. Frequency-domain analysis is useful even when controller design is performed in the time domain. The recent theory on robustness of control systems is one such example. What is probably more reasonable is to replace such exercises as inverting Laplace transforms and the like with instruction on the use of frequency-domain techniques for performance and robustness analysis.

Why should the undergraduate curriculum have to wait until the year 2000 to include a treatment of model uncertainty and constrained control? While a thorough treatment of these topics is probably most suited for graduate level courses, there is enough existing theory to justify, at the very least, a conceptual introduction to these subjects.

Lin Tung: Fisher Controls

ChE's should understand the process as well as control and should have some background in control strategies for various unit operations. Increased use of the concepts should not be at the expense of process understanding. PID control will still be a key control concept in 2000 (and probably not be replaced by nonlinear programming), although as part of distributed control systems (DCS). DCS system concepts should be presented and students should be exposed to such equipment (most vendor systems employ the same basic ideas although the equipment may look different). We need to upgrade the operator's educational level; in Europe BS engineers are used (why use a high school graduate to control a multimillion dollar process?).

Ed Bristol: Foxboro

Teaching of PID tuning should have a strong root locus component (the closed-loop response is shaped by the dominant three poles). We need to get students to think more in the frequency domain and to develop a practical feel for dynamics and control. An experienced tuner is like an experienced car driver. Theory should be used to gain insight, not just to implement a tool. Control engineers should not restrict themselves to facts that can be proven mathematically. We want methods that work even when the theory does not. Model uncertainty (such as nonlinearity, model order, or noise) should in practice lead one to use a simpler approach, while many theories tend to give more complex answers.

Christos Georgakis: Lehigh University

Regarding the observation that we might abandon the continuous time domain for the discrete time one, you are right that the widespread use of digital control computers is pushing us in this direction. However, many chemical processes are slow, and if slow composition measurements are not used, then the sampled character of the digital control computer has no effect on the performance of the controller. In this case, continuous time might be sufficient. I, however, agree with you that the sampled data concerns should start being incorporated in the first process control course. The extent will depend on what is the philosophy of the most popular texts between now and the year 2000.

I expect that "expert systems" will have an impact on process control education much earlier than the year 2000 and to a larger extent than you estimate in your paper. In my definition of "expert systems" I include systems that are not necessarily "expert" but complement the numerical calculations, of, say, a PID algorithm with symbolic calculations (or logic, if you wish) to design the overall control system. A selector is the simplest example. While in practice we use override controls and PLCs, we do not teach our students about them in a systematic way.

Joel Hougen: Consultant (U. of Texas, retired)

We need to strongly emphasize accurate instrumentation and the importance of obtaining good data. Many existing plants are instrumented without much thought about needed performance characteristics. Students need to appreciate the importance (and lack) of field instrument calibration and the difficulty of obtaining fundamental plant models (hard to predict steady state or dynamic characteristics in advance). Undergraduates should have the experience of successfully verifying simple dynamic models in the laboratory. A reasonable goal is ±2% accuracy in material balances. For most processes, simple dynamic models are adequate and PID controllers are satisfactory. However, Ziegler-Nichols tuning is not appropriate for today's controllers to achieve high performance. A great amount of process understanding is necessary to develop process control strategies; algorithms are secondary. In the course, theory should connect to reality (and not just be a mathematical exposition).

George Stephanopoulos: M.I.T.

Prerequisites for the design of good controllers are: the in-depth understanding of open-loop process dynamics and closed-loop behavior under various control modes (proportional/integral/der-ivative). A good coverage of these two subjects gives a strong imprint of analytical attitude, which completely characterizes the educational experience in the course.

But within such an environment the following issues are hardly ever raised: What are the operational objectives in the plant? How does one convert informal operating requirements (e.g., minimize operational cost) to formal and explicit control objectives?

Even for the design of single loops, asome important considerations are only lightly touched upon. For example: How does one systematically develop the process model needed for a particular control task? What is the effect of model inaccuracies on the stability and performance robustness of a control loop? How does one design a control loop in the presence of input and output constraints?

While the above questions are asked by practicing engineers on a daily basis, it is not true that they are difficult to answer or require an extensive expansion of lecture hours.

The continuing preoccupation with the analytical leg of process control is partly due to our inability to deal with non-analytic, factual, poorly articulated, often contradictory and qualitative knowledge. We do not know how to handle conflicting facts, or we downplay the importance of qualitative knowledge. Our ability to harvest the added opportunities offered by knowledge-based systems depends on our awareness of the new computing technology. Object-oriented programming is indispensable in capturing structured knowledge around processing units, controllers, control design tasks, order-of-magnitude reasoning, etc.

Yaman Arkun: Georgia Tech

Dynamic modeling should be covered throughout the ChE curriculum. The control course should focus on the utilization of dynamic models for control purposes rather than setting them up from first principles which can be best accomplished in other core ChE courses. It is better to spend the time on relevant control issues like the extent of required modeling sophistication, e.g., nonlinear vs. linear approximations, effects of parameter uncertainties, neglecting secondary physical phenomena, etc.

I personally do not devote more than two lectures to Laplace transforms. I believe the home for detailed treatment of Laplace transforms is in a math course. However, the topic is important as it naturally bridges linear dynamic models with continuous transfer functions and frequency response analysis. The emphasis on frequency response should remain since practical and fundamental problems such as stability, performance, and robustness with uncertainty can be nicely interpreted using Bode, Nyquist plots, and M-circles without resorting to trial and error dynamic simulations.

In the very near future, I believe we will see more coverage of discrete-time systems and model predictive control in the undergraduate control courses. The reason for this is the industrial success of MPC and the fact that it does provide a framework within which a wider scope of realistic control problems can be conveniently couched and conveyed to the students. The issues of process economics, operational constraints, changing objectives with time, and the utilization of process models online are difficult if not impossible to illustrate using PID or other more classical controllers. Any undergraduate textbook in this area will have to be supplemented with simulation software which implements MPC. Development of case studies mimicking the exercise a control engineer goes through in practice will be invaluable. Such projects would be assigned at the beginning of the course very much like a senior design project and solved in parallel with the lectures covering areas such as problem formulation, model development and discrimination, control structure selection, and finally, tuning and performance assessment. We have done this using PID, feedforward, and cascade controllers, and I can envision doing it in the near future using MPC and more challenging industrial problems. ❐