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A global view of graduate process control education

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Abstract

This paper reviews the status of graduate level process control education and surveys graduate process control offerings for more than 50 chemical engineering and control engineering departments throughout the world. There apparently has been no such survey conducted in over 10 years. Courses are categorized by their content and focus (selected topics versus integrated subject), use of case studies and projects, and the presence of a laboratory component. Observations on how graduate education varies around the world are made, and the influence of interdisciplinary control engineering degree programs is discussed. New possibilities for content delivery via distance education are described, and the feasibility of web-based shared curriculum content (a virtual textbook) is explored. Finally we present the industrial view of desirable attributes for Ph.D. graduates in the systems area.

Keywords: Laboratories; Simulation; Virtual textbook; Distance education; Employment

1. Introduction

In contrast to undergraduate process control education, the status of graduate process control education has not received much evaluation in the past 20 years. The reason for this lack of attention may be because graduate degree requirements usually consist of only a few required courses and in the USA are not subject to pressures such as accreditation. As a result, course offerings tend to be quite diverse in content. The core of the graduate chemical engineering curriculum typically includes transport phenomena, thermodynamics, and reaction engineering, but not process control or systems engineering. Beyond the core curriculum, students take additional courses that are invariably related to their research specialization. The typical chemical engineering student in the systems area takes an above average number of courses in departments such as electrical engineering (EE), mechanical engineering (ME), and aerospace engineering (AE).

In the previous six CPC conferences, there were no papers presented on graduate control education; with the exception of a panel discussion at the 1995 American Control Conference, which is summarized in the next section, there have been few other venues where graduate control education has been discussed. It therefore appears that a comprehensive assessment of graduate process control around the world would be timely, using a survey of control and systems faculty as the primary vehicle for collecting information. Given this global view of process control education and the potential of information technology to expand the reach of a single faculty member to students at other universities, we believe that the results of this survey can lead to increased collaboration of faculty in classroom teaching, in cooperative development of educational materials, and in research. In addition, from a limited survey of employers of Ph.D.'s in the systems area, we have identified skills expected in those graduates that should be incorporated into their training.

After providing a historical perspective on control education, we summarize the results of the survey and dissect important components of graduate control courses. These components include use of laboratory experiments; case studies, projects, and simulation problems; potential development of a virtual control textbook and distance education to share existing courses with multiple departments; and the industrial viewpoint of graduate control education.

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1.1. Ghosts of graduate control courses past

During the past 40 years, some consensus has been reached on what should be included in the undergraduate control curriculum, but not for the graduate curriculum. The Mellichamp (1995) survey of eight U.S. departments presented at the 1995 American Control Conference indicated that there was little agreement on graduate course content. Efforts in course development were fragmented, and there were no control textbooks enjoying widespread adoption at the graduate level. Mellichamp also reflected on some key defining attributes of the process control community, namely: it is a small, tightly connected group that is fairly close to industry and industrial practice, with cross-disciplinary links to fields like electrical engineering and mechanical engineering. At that time he felt that the control field was not viewed by other chemical engineering faculty as being at the core of chemical engineering. For example, seldom was there a required graduate course in the control or systems area for students outside the control area.

The respondents to Mellichamp's survey did not agree on the primary objective for the graduate process control course; instead several different objectives were listed, depending on the department:

(1) fundamental background material for all chemical engineering students,
(2) methodology-based material for future control practitioners,
(3) theoretical material serving as preparation for doctoral research,
(4) numerical/computational content to perform simulation, optimization, or control.

This lack of pedagogical agreement in turn led to four different approaches in course design:

(1) teach a fundamentals course intended for a general chemical engineering audience,
(2) provide a collection of "advanced" control topics,
(3) teach theoretical control material for research preparation under specific professors,
(4) avoid it altogether and send control students to other departments, e.g., electrical and mechanical engineering.

Topics covered in fundamentals courses included: linear state-space analysis, modeling physical systems, matrix exponential function, transfer function, matrix representations, realization theory, controllability and observability, stability of linear time-invariant (LTI) systems, feedback control and pole placement designs, LQR/LQG and robust designs, discrete time systems, and degrees of freedom and controller structures. In most courses numerical and computational materials (MATLAB + Toolboxes) were introduced in parallel with concepts/theory. There was increasing emphasis on practical applications of control even for very theoretical topics.

Survey respondents cited a number of texts/reference books that in 1995 were suitable for chemical engineering graduate coursework: Astrom and Wittenmark (1990), Ljung (1987), Soderstrom and Stoica (1989), Morari and Zafiriou (1989), Prett and Garcia (1988), Shinskey (1984) and Deshpande (1985). Undergraduate texts that contained advanced material for discussion of specific topics were also cited: Smith and Corripio (2005), Seborg, Edgar, and Mellichamp (2004), Luyben (1990), Ogunnaike and Ray (1994), and Marlin (2000). In 1995 no author or group of authors was apparently writing the "definitive" text for the graduate control course; there was not a big enough market, and little consensus existed on what should be included for widespread adoption.

Mellichamp suggested that a virtual (versus traditional) graduate text could be attractive because a dynamic text that grows with the field would track changing technology, cover a wide range of topics, and avoid the constraints of conventional textbooks. In addition, there would be no fixed production (printing) schedule, so it could remain current with maturing information technology tools. The collected content could take full advantage of simulation, graphics and animation. Many younger authors might have the time to contribute a chapter or two (versus writing a complete book). Such a text would be accessible to faculty and students, so cost to users would be very low.

Key disadvantages of a virtual book include the difficulty of recruiting busy faculty to write such materials, enforcing quality and consistency for all authors, and providing a financial reward for authors. Mellichamp concluded that a virtual textbook in control was feasible in 1995 but no course of action was proposed.

1.2. Survey of systems and control faculty

In preparation for CPC7, faculty at over 80 departments of chemical engineering and control engineering worldwide were contacted by the authors, using the questions shown in Table 1.

Table 1
Questionnaire on graduate control education

1	List process control and related courses taught at the graduate level in your department; attach a syllabus if available. How often is each course taught (e.g., once per year)? What faculty are involved? Does the course attract many students outside of chemical engineering?
2	What textbook(s) if any are used in the graduate process control course? What other resources are used in this course?
3	What are the objectives of the graduate course (list up to four)?
4	List courses that graduate students in process control normally take at your university. How many courses are typically taken by M.S. and/or Ph.D. students?
5	Are there any laboratory courses that control students take at an advanced level? If yes, briefly describe the nature of the experiments
6	Are projects an integral part of the graduate control course? Give some examples of projects assigned recently
7	Do you use simulation case studies in the graduate or undergraduate course in control? Describe any model processes you have used recently, especially from non-traditional areas of chemical engineering
8	Can you suggest content which faculty from other universities can share in the graduate control course? Have you collaborated with outside faculty in your teaching? Would you consider contributing to or using a virtual (electronic) textbook for the graduate control course?
9	Have you taught a control course using a distance education format, i.e., to industrial participants? If so please briefly describe the specific format and the reason for choosing such a format

Information from over 50 responses have been compiled and are reported in the sequel.

2. Overview of graduate control courses offered

First it should be made clear that “graduate control” can refer to a course covering more than just feedback control and can include modeling, identification, and other topics, perhaps a better descriptor is graduate systems course. In assimilating the survey responses, it appears that graduate courses currently can be grouped into two main categories: (1) selected topics, which do not have to be connected to each other, and (2) integrated subject, where the course has a single theme often based on a primary textbook. Of course the distinction between these two categories may be a little fuzzy in some cases.

Similar to the situation 10 years ago, the current systems courses are not viewed as core courses for chemical engineering graduate students. Given that all areas of the chemical engineering profession increasingly rely on modeling as a tool, it is surprising that few departments offer a general course on modeling for their graduate students. The fact that many departments only offer one systems course per year means that the tension between teaching selected subjects in depth versus introduction of new research results still exists in many departments. However, as discussed below, a broad control curriculum can be established by using control faculty in other engineering departments.

2.1. Selected topics courses

Table 2 provides a summary of the selected topic courses reported by the survey respondents. These courses often arise because the department can only offer a single course in control, thus it will have multiple objectives. There are fewer courses of this type reported than the integrated subject type, which is discussed in Section 2.2. Table 2 identifies the different topics covered in each course using acronyms. Topics like multivariable control (MVC), identification (ID), advanced single loop control (AC), digital control (DC), and model predictive control (MPC) are fairly popular; but beyond these topics, there is considerable diversity. In several cases the collection of topics comes after what is taught in the basic undergraduate control course, and thus can be based on the second half of textbooks such as Ogunnaike and Ray (1994), Marlin (2000), and Seborg et al. (2004). Most instructors teaching selected topic courses use notes instead of a textbook. Only three departments with active control researchers indicated that they did not teach a graduate control or systems course.

2.2. Integrated subject courses

This type of course tends to be the preference of most instructors, especially when a department can offer more than one systems or control course. From the survey, the clear leader is a course in multivariable control using the textbook by Skogestad and Postlethwaite (2005). Other popular choices for integrated subject courses include identification, nonlinear control, model predictive control, and optimization. When there is a strong control presence in such affiliated departments as mechanical engineering or electrical engineering, the tendency is for the chemical engineering department to become more specialized in its graduate course offerings, which can change from year to year. Having more than one faculty member in the control area usually increases the number of specialized offerings. Other than the textbook mentioned above, there is tremendous diversity in the textbooks chosen, as is evident from Table 3 and about 25% of the courses are based on notes instead of a single textbook. About one-third of the chemical engineering departments who responded teach more than one control course. McMaster, Alberta and National Taiwan UST teach four courses; five departments (DTU, Ecole Polytechnique Montreal, South Carolina, Texas Tech, and Waterloo) teach three courses. Excluded from this list are interdisciplinary control engineering departments, who usually offer more than 10 courses (see Section 2.3).

Table 2
Selected topics courses in control

Aachen	AC, DC, FR, MVC, NC MVC, OP, PC
Alberta	SA, FD
Arizona State	DC, FR, ID, MVC, MPC, SS
CMU	AP, ID, MPC, NC MD, OP, SM
CUNY	ND, PC
Hong Kong	AC, BPC, DC, MPC, MVC, PM
U. Houston	DC, ID, MPC, MVC, PM, RPC
Illinois Inst. Tech	MPC, SS
IIT Kanpur	MPC, MVC, PC
Imperial	AC, ID, PC
KAIST	AC, BPC, MVC, OP, PC
McMaster	DC, MPC, SS AP, MVC, SC
NTUST	AC, BPC, DC, MPC, OP, PM OP, PC, SM
Oklahoma State	AC, CA, DC, MVC
Pisa	FR, MPC, MVC, RPC AC, ID, MPC, SM
RPI	ID, MVC, SS
S. Carolina	DC, MPC, OP
SNU (Seoul)	AC, FR, MVC, MPC, PM
TAMU	NC, ND, OC, SS
Texas Tech	DC, MPC, OP, SPC MD, MPC, OC
Tsinghua	AC, DC
U. de los Andes	AC, MPC, MVC
UCSB	ID, MPC, MVC, PM
U. Massachusetts	AP, DC, ID
U. Texas	ID, MPC, PM
U. Washington	BPC, DC, ID, MPC, PM
Waterloo	MPC, NC, RPC AP, DC, ID, MVC, OC, SS

Acronyms are used to identify specific topics as follows—AC: advanced control; AP: adaptive control; BPC: batch process control; CA: control applications; DC: digital control; FD: fault detection; FR: frequency response; ID: identification/estimation; MD: modeling; MPC: model predictive control; MVC: multivariable control; NC: nonlinear control; ND: nonlinear dynamics; OC: optimal control; OP: optimization; PC: plantwide control; PM: process monitoring; RPC: robust process control; SA: statistical analysis; SC: stochastic control; SM: simulation; SS: state space analysis; SPC: statistical process control. Some universities teach more than one selected topics course (shown as two lines).

Table 3
Integrated subject courses in graduate systems or control and primary textbooks

Alberta	Multivariable Control—Skogestad and Postlethwaite (2005) System Identification—Ljung (1987)
Arizona State	System Identification—Ljung (1987)
CMU	Advanced Process Systems Engineering—Biegler, Grossmann, and Westerberg (1997)
Delaware	Multivariable Control—Skogestad and Postlethwaite (2005)
Drexel	Nonlinear Model-Based Control
DTU	Optimizing Plantwide Control Chemical Plant Operations Multivariable Process Identification
Ecole Polytechnique Montreal	Optimal Control—Bryson and Ho (1981) Model Predictive Control—Rossiter (2003) Identification and Control of Bioprocesses—Baston and Dochain (1990)
Georgia Tech	Model Predictive Control—Morari et al. (in press)
Imperial	Advanced Process Operations
Kyoto	Multivariable Control—Ohshima (2000)
Lehigh	Multivariable Process Control—Skogestad and Postlethwaite (2005) Nonlinear Systems Analysis—Khalil (2001) Model Predictive Control—Morari et al. (in press) and Camacho and Bordons (1999)
Manchester	Process Control in Pulp/Paper
Maryland	Optimization—Edgar, Himmelblau, and Lasdon (2001)
McMaster	Optimization of Chemical Processes—Nash and Sofer (1996) and Wright and Nocedal (1999) Time Series Analysis/Process Identification Process Control Design—Skogestad and Postlethwaite (2005) Multivariate Statistical Methods
NTNU	Multivariable Control/MPC—Skogestad and Postlethwaite (2005)
NTUST	Multivariable Control—Skogestad and Postlethwaite (2005) Process Simulation—Luyben (1990, 2002) and Bequette (1998)
Pittsburgh	Robust Process Control—Skogestad and Postlethwaite (2005) Nonlinear Dynamical Analysis—Khalil (2001)
Purdue	Optimization of Chemical Processes—Ravindran, Ragsdell, and Reklaitis (2006)
RPI	Model Predictive Control
S. Carolina	Robust Control—Skogestad and Postlethwaite (2005) Nonlinear Control—Khalil (2001) and Isidori (1995)
S. Florida	Model-Based Process Control—Brosilow and Joseph (2002)
Texas Tech	Linear Chemical Process Control—Rugh (1995) and Antsaklis and Michel (2005)
Tsinghua (Taiwan)	Engineering Optimization
UCLA	Nonlinear Systems and Control—Khalil (2001) and Christofides and El-Farra (2005) Control of Infinite Dimensional Systems—Christofides (2001)
UCSB	Process and Control System Monitoring Systems Biology
U. de Los Andes	Process Control II Optimal Control
Utah	State Space Methods—Rugh (1995) Robust Multivariable Control—Skogestad and Postlethwaite (2005) and Zhou and Doyle (1997)
Waterloo	Statistics in Engineering
Wisconsin	Model Predictive Control
Zhejiang	Robust Control Theory Predictive Control Optimization and Optimal Control

Courses shown under one university are not necessarily taught each year and may vary from year to year. If no textbook is referenced, then course notes are used.

Almost all universities report that their students take quite a few courses outside of the home chemical engineering department, typically 6–10 courses. In some cases there is a rotation among two or three departments to offer basic systems courses such as state space analysis and/or linear systems every second or third year. Some ad hoc scheduling of control-related courses occurs in many departments, but in a few cases there is a well-articulated set of ten or more courses, UCLA offers 13 courses, which are co-listed under all participating departments (EE/ChE/MAE): linear systems, linear optimal control, optimal control, robust control using convex methods, stochastic control—I, II, III, linear programming, nonlinear programming, dynamic programming, infinite-dimensional programming, nonlinear systems, nonlinear control, control of infinite-dimensional systems, and adaptive control. UCSB is another good example, see www.ece.ucsb.edu/∼hespanha/ccec. A number of universities have chosen to set up a separate control engineering degree program which affords the most organized approach to graduate course offerings in control. This type of program is discussed in the next section.

2.3. Interdisciplinary control programs

A number of process control researchers are affiliated with interdisciplinary control programs or institutes: EPFL, Manchester, NTNU, Oklahoma State, Villanova, Stuttgart, Tsinghua, and Zhejiang. Most of these programs have an advantage of a relatively large number of faculty to teach the courses offered. Typically four to six control courses are required for the M.S. degree, but some institutes offer many more than six different courses, e.g., advanced process control, control of nonlinear systems, digital control, digital signal processing, estimation theory, identification and control, instrumentation, linear systems, model predictive control, modeling, multivariable control, optimal control, process monitoring, robust control, stability, and stochastic and adaptive control. This type of program occurs more frequently outside the USA. The only interdisciplinary control programs with a process control flavor in the USA known to the authors are at Oklahoma State and Villanova University. In both cases all of the control offerings in chemical, mechanical, and electrical engineering have been combined into a coherent program of coursework. We observe that when such a separate control department exists, then the Department of Chemical Engineering at that university tends not to have faculty or courses in the control area.

2.4. Multi-university intensive courses

One other model that involves multi-university cooperation is to hold a 1- or 2-week intensive course in the systems area. In this case graduate students would travel to a central location for the course, which would have a fairly large group of instructors. The Ph.D. school in Industrial Process Control or CIP (organized by Claudio Scali at Pisa and Roberto Baratti at Cagliari) presents an update on basic methodologies and advanced techniques in process control; see http://cpclab.ing.unipi.it/cip/index.html. The audience is Ph.D. students in Chemical Engineering in Italy, whose education in process control varies greatly from one university to another. At the moment only 5 of 15 Italian universities give graduate courses in process control.

This school is linked with two other Ph.D. schools; each course is given every 3 years: AMO (organized by Milano-Politecnico) is oriented towards analysis of data, optimization, and data reconciliation, while ADP (organized by Napoli and Benevento) covers problems and methodologies for the analysis of process nonlinearities. The CIP school lasts 5 days with lessons in the morning (4 h) and exercises/case studies in the afternoon (3 h) for a total of $7 \times 5 = 35$ h. This workshop has attendance of about 30 students from all over Italy and takes place in June in Sardinia. The contents include identification, MIMO processes, nonlinear control, model predictive control, and control applications. The fifth day is usually reserved for visiting researchers in related fields; CIP in 2005 featured Jose A. Romagnoli – Sydney (process monitoring) and Jesus Alvarez – Mexico City (optimization of batch processes).

In the Americas, advanced graduate students, postdoctoral fellows and young researchers recently participated in the Pan American Advanced Studies Institute (PASI) on Process Systems Engineering, which was funded by the U.S. National Science Foundation and the U.S. Department of Energy. The workshop took place at Iguazu Falls, Argentina, on 16–25 August 2005, and consisted of lectures and seminars in the areas of optimization, process and product design, process and supply chain operations, and process dynamics and control. See http://cepac.cheme.cmu.edu/pasi.htm for the detailed program. The time allocated for lectures included exercises, case studies and/or demonstration of computer tools. There were 22 lecturers from universities in South and Central America, Canada, and the USA. The Pan American Advanced Studies Institute provided full or partial financial support to eligible students from the Americas to cover transportation and/or accommodation (double occupancy) and meals. There was a limit of 50 students, with about 50% coming from the U.S. the organizers of PASI were Ignacio Grossman, Carnegie Mellon University, Jaime Cerdá, INTEC (UNL-CONICET), and Jose Pinto, Polytechnic School of the University of Sao Paulo in Argentina.

We conclude that the generally specialized nature of graduate control education makes offering a course to students at more than one university attractive, in order to enrich the overall coursework program for these students. This practice is convenient when two universities are close to each other (e.g., University of Pittsburgh students taking a course at Carnegie-Mellon University). Another option is to use electronic delivery of courses, as discussed in Section 4.2. Finally selected educational materials from different courses could be assembled together in a virtual textbook, such as discussed in Section 4.1.

3. Laboratories, case studies, course projects, and simulation examples

3.1. Laboratory experiments

Not many graduate programs provide a course-based laboratory experience in process control for their students. This is not particularly surprising since many process control students carry out experimental control research as part of their thesis or dissertation. Of the respondents, only the following schools offer a laboratory course: University of Manchester, Universidad de Los Andes, Technical University of Denmark, Stüttgart, University of Utah, Oklahoma State, University of Alberta, Lehigh, EPFL, Waterloo, and Ecole Polytechnic-Montreal. Some departments use non-chemical engineering experiments (such as the inverted pendulum), especially those offering interdisciplinary control degrees. Clearly most universities rely more on simulation as a tool for teaching control. However, it is useful here to highlight several universities who have an enriched laboratory experience.

Lehigh offers annually a joint chemical/mechanical engineering laboratory that is available to advanced undergraduate and first year graduate students. The lab has 11 experiments available, five to six of which may be covered during a given semester. Possible studies include PRBS tests, relay feedback, stability tests, and PLC for a machine tool robot. At University of Alberta both graduate level courses have laboratory components that require students to experimentally evaluate an advanced control technique of their choice on pilot scale processes or collect open or closed loop data for identification purposes. Often industrial data is also used for student training. At Ecole Polytechnique Montreal lab experiments are assigned to students taking Cell Culture and Identification and Control of Bioprocesses. The experiments consist of designing and evaluating control strategies for environmental variables like dissolved oxygen and pH. At Technical University of Denmark, the course "Chemical Plant Operation" introduces students to a practical plant, e.g., an energy-integrated distillation column including measurement, control, and safety supervision system. Topics that can be covered include calibration procedures for measurements, construction of control loop diagrams, introduction to plant control hierarchy, safety aspects, production planning and the effect of scheduling on plant operation. Simulation of plant operation in selected operating regions is carried out, and operator-controlled and automated start-up and operation shutdown are executed.

In the masters level courses at EPFL, laboratory experiments are designed to demonstrate important dynamic characteristics of real processes, such as actuator saturation, measurement noise and nonlinear effects. To meet the needs of a student population with diverse engineering backgrounds, a number of mechatronic, hydraulic and thermal systems are utilized. In all, 13 different physical processes are used to support the laboratory experiments. Laboratory work is mandatory for all students in the sixth semester. The number of hours of laboratory work taken by a student depends on the engineering discipline. Each academic year about 150 students enroll in the laboratory classes and perform an average of 10 h of work. All experiments are equipped with a complete data-acquisition and control system integrated in a single workstation. Industrial electronic controllers are also used to familiarize students with commercially available equipment. The servo drive, the process trainer and the inverted pendulum experiments are accessible either locally or remotely through the eMersion portal (http://lawww.epfl.ch/page13172.html). At Stuttgart (Institute for System Theory), laboratory experiments are normally conducted in conjunction with several control theory courses, e.g., MIMO control of a distillation column and control of an inverted pendulum.

3.2. Simulation examples used in graduate control courses

While the use of simulation is pervasive in control education in general, it is particularly so with the graduate course. Virtually all respondents indicated that control system evaluation using simulation was central to the course. In response to the question about the use of simulation case studies involving specific processes, about half of the respondents incorporate this particular component in their courses. A list of the specific simulation case study processes reported is shown in Table 4 along with the respondent's name (contact person) and institution. A few institutions do not use simulation case studies because they have access to pilot plants and industrial data; nevertheless, even

Table 4
Simulation examples used in graduate control courses

Process	Institution/contact
Polymer Film Extrusion/Film Diffusion	Illinois-U.C. (Braatz)
Skogestad Distillation Column	Utah (Skliar), Arizona State (Rivera)
Naphtha Cracker, Shell Oil Fractionator	South Florida (Joseph)
Shell Oil Fractionator	Georgia Tech (Lee), Aachen (Marquardt), Arizona State (Rivera)
Tennessee Eastman Process	South Florida (Joseph), Manchester (Lennox), U. Texas (Qin)
Steam Turbine Process	Manchester (Lennox)
Fermenter, Blood Pressure Control System	Texas A&M (Hahn)
Biochemical Reactor	U. Massachusetts (Henson), Pittsburgh (Parker) Ecole Poly. Montreal (Perrier), DTU (Jorgensen)
Semiconductor Wafer Baking	NU Singapore (Ho)
Chemical Reactor (CSTR), pH System	U. de los Andes (Camacho)
Chemical Vapor Deposition	Georgia Tech (Gallivan)
Lime Kiln, Tubular Reactor	U. Waterloo (Budman)
HDA Process (HYSYS)	IIT Kanpur (Kaistha)
Tubular Reactor, Azeotropic Distillation,	NTUST (Chien)
Reactive Distillation, Hydrodealkylation,	NTUST (Chien)
Ethyl Benzene	NTUST (Chien)
Chemical Vapor Deposition, Epitaxy	UCLA (Christofides), Arizona State (Rivera)
Auto Thermal Reforming Reactor	Ill. Inst. Tech (Chmielewski)
PCM Case Studies, Diabetic Patient	Pittsburgh (Parker)
Kidney Filtration, Cardiovascular Model	Texas Tech (Hoo)
Perfusion Bioreactor, Bleaching (Pulp/Paper)	Ecole Poly. Montreal (Perrier)
Plant/Mammalian Cell Cultures	Ecole Poly. Montreal (Perrier)
Injection Molding	Hong Kong (Gao)
Semiconductor Operations	Tsinghua (Jang)
Heat-Integrated Distillation	DTU (Jorgensen)
Chemical Reactor, Polymerization	Kyoto (Ohshima)
Batch Distillation Column	EPFL (Bonvin)
Drug Infusion, Blood Glucose Regulation	RPI (Bequette)

some departments with a strong laboratory component, such as the University of Manchester, indicated that they still find it useful to incorporate simulation case studies.

The case study simulation examples noted in the responses are mostly standard chemical engineering unit operations: distillation columns, chemical reactors, pH process, and the like, with a few somewhat less common examples such as polymer film extrusion and the lime kiln process. A few institutions use plant-wide simulations for their case studies, such as the well-known Tennessee Eastman process, the Shell fractionator, or HYSYS. Some departments, mostly from the Far East, use examples from the microelectronics industry. Case studies involving biological processes are relatively few, but several respondents indicated that they are developing more simulation case studies along these lines. It appears that the most extensive use of simulation case studies is to be found at the National Taiwan University of Science and Technology (NTUST), with six case studies. In virtually all cases, the preferred platform for deploying these simulation case studies has been SIMULINK. Several of the respondents indicated a willingness to share their resources with others.

It is our opinion that simulation case studies are important in their own right in preparing students for industrial careers (not just as a surrogate when using real experiments is not possible). This is because many advanced industrial groups make use of realistic simulations as an integral part of operator and support engineer training; presenting simulation case studies in this light should be an important part of the control engineer's training.

4. Sharing curriculum materials, courses and students

4.1. Development of a virtual textbook

The idea of a virtual graduate control textbook was discussed earlier in Section 1.1. Many of the same advantages discussed 10 years ago by Mellichamp (1995) still hold. About two-thirds of the 50 survey respondents expressed interest in using materials from such a content collection or in contributing materials. Given the diversity of graduate control courses taught currently, there is indeed a wealth of information available and many interested participants.

It is instructive to review one recent experience in developing a molecular simulation virtual textbook, which is relevant to developing a virtual textbook in graduate level control. Under the NSF grant, "World Wide Web-Based Modules for Introduction of Molecular Simulation into the Chemical Engineering Curriculum", seven university experts in molecular simulation under the auspices of the CACHE Molecular Modeling Task Force (MMTF) have developed web-based modules to facilitate introduction of molecular simulation into the chemical engineering curriculum. Modules contain instructor materials, fundamental tutorials, student problems, and assessment materials. These teaching modules can be integrated directly into chemical engineering core undergraduate courses, supplying for the instructor and the student the appropriate linkage materials between macroscopic concepts currently taught in these courses and molecular simulations. Modules are centered around Java applets that run the molecular simulations and provide an "experimental" simulation platform for students to explore concepts. Note that if this were done in the control area, MATLAB would be the de facto standard for simulation examples.

The MMTF designed a consistent web-based interface that organizes all of the material in each module and developed scripts using *perl* that ease the job of putting the written material into this common format. The developer of a module must construct simple text files, perhaps with HTML markup that permits inclusion of figures and tables. Then he or she runs the files through the *perl* script, which adds HTML formatting and links to put the set of files into the common configuration. The files are uploaded to the module site for anyone to access. This site is perhaps best accessed through the *Etomica* site http://www.ccr.buffalo.edu/etomica. *Etomica* is a Java-based support environment developed for the modules project. Provided with each module are:

- background materials on the concepts taught by the module,
- a molecular simulation that permits the user to explore the concepts taught,
- tutorial material that illustrates the use of the simulation applet,
- additional problems for use as homework problems,
- assessment form (in development and not currently available).

It is possible for a course instructor to tailor the book to his or her needs, even to the point of setting up a specialized table of contents for the course. The arrangement ensures a consistency in formatting, and allows the presentation to be modified easily. In the same vein, changes in HTML standards (which govern the "language" read by the Web browsers) can be readily accommodated, and improvements in Web-browser designs can be rapidly exploited. Contributors are not required to provide content formatted with HTML mark-up, and a dedicated staff person is not needed to do extensive clean up and formatting of new contributions.

Based on the graduate control survey, it appears feasible to develop a virtual textbook in control, because there are 20–30 faculty interested in participating in such a project. A task force under the CACHE Corporation has been formed to develop this idea further.

4.2. Distance education approaches for graduate systems education

Distance education has been defined as any formal approach to learning in which a majority of the instruction occurs while educator and learner are at a distance from each other. There are a variety of delivery techniques for this educational approach, depending on the time-space coordinates that are employed. While there has been much publicity (and some hype) about distance education, there needs to be a more thoughtful approach to distance learning at the graduate level. Simply putting textual information and power point slides on a web page is not a substitute for lecture-based education.

Using distance learning to access experts at other universities is an appealing idea. Anyone who has listened to a Pavarotti CD but never heard the great tenor in person has certainly received a certain level of enjoyment (and perhaps inspiration) from that experience. Based on this analogy, faculty who suggest education can only be delivered in the traditional face-to-face mode are thinking "inside the box". We ought to seek ways to enhance the classroom experience for graduate students through use of distance education tools, in a hybrid approach that combines distance and face-to-face learning with web-based content. We anticipate that many instructors in the systems area would be delighted to team-teach a course with a collaborator at another university, assuming the required technology is not too expensive, not an impediment, or not a lot of additional work. Combining two classes where the resulting enrolment is still less than 20 students would be quite manageable and might even reduce the workload for the faculty involved.

While not strictly falling into the area of distance education, a number of departments reported that they give industrial short courses on a variety of topics and sometimes oriented towards specific industries (e.g., control of semiconductor production). These universities include McMaster (clear leader with over 100 courses, mostly on-site), Technion, Alberta, Illinois/Delaware/Georgia Tech, Tsinghua (Taiwan), and UT-Austin.

Another model that may be economically attractive is the concurrent offering of residential classes and off-campus courses to industry. These classes could include advanced undergraduate courses and graduate courses. Such an approach has been used with varying frequency at several chemical engineering departments, such as University of Delaware, Lehigh University, and University of Texas. This mode of instruction provides a different type of revenue model, where faculty can receive extra compensation for the additional courseload. It is not unreasonable to believe that faculty from around the U.S. could even form virtual chemical engineering departments in the future.

Several departments carry out various forms of delivery for distance education in regular courses, using webcast (South Carolina, Tsinghua, Manchester, Villanova, Arizona State), CD-ROMs (Oklahoma State), and videotapes (Texas Tech). In most courses a few students in industry are involved in addition to on-campus students. In some cases students come to campus periodically for special programs or to take exams. At Arizona State and Villanova, online courses and materials are provided through a high-speed Internet connection. Lectures are presented via streaming media and includes video along with other visual materials as seen in the classroom. Books, exams, and course packets are still paper-based. At Lehigh University CHE/ME/ECE 434 has been offered via satellite in a distance education format several times and viewed at Merck, Rohm and Haas, and Air Products. The tapes are currently being used in a web-based course offering for distance education students as well as on-campus students. The instructor (M.V. Kothare) only had to set up homework, course projects, etc. but not the lectures which are the tapes. One survey respondent indicated that a European cooperative program with a distance education component is under development, to be led by Lund Institute and Stuttgart.

Control System Engineering courses are delivered to distance learners within the Oklahoma State University (OSU) system by live two-way interactive videoconferencing. OSU connects to eight remote sites within the State of Oklahoma through a state-owned and operated fiberoptic network known as OneNet. Corporate and public sites can link to this network to receive courses that originate from an OSU studio or any other point on the network. While the system has capabilities to carry both full-motion and compressed video, the more common of the two is compressed video, which reduces the amount of bandwidth needed to send the signal. Typically all remote sites have at least one site-coordinator who can assist with technical problems during the class and facilitate transfer of homework and proctor exams. Each site also records the video broadcast so students have access to classes that they may miss due to work requirements. In cases where no other delivery method is available due to location or scheduling, a degree-seeking student may enroll in an MSCSE course through videotape. Master videotapes are by-products of distance learning courses originating in an on-campus studio. Videotapes are copied by Engineering Extension and sent overnight to remote students. Typically, students will receive the tape within two working days of the live class. The tapes remain in the student's possession until the end of the semester, when they are returned at the student's expense.

In 2002 an upper-level graduate elective course (CHEG 801) taught by Frank Doyle (then at U. Delaware) used live video streaming as well as an online course management software package developed at the University of Delaware. The graduate course had a population consisting of local graduate students and continuing education professionals, as well as graduate students and professionals at a distance. Distant locations included Indianapolis and Seattle, so time zone differences were a consideration as well. Using RealPlayer formatted video, lectures were streamed live over the web during normal class time and simultaneously archived an electronic version that was accessible from the syllabus page. It was desirable to offer a variety of media for access, especially for local students, in order to respect diverse talents and ways of learning.

Professor Doyle's biggest fear was that the archived video would promote absenteeism, but attendance was nearly perfect, and web access statistics revealed that the local students were using the archived video as a review tool. The distance education students were able to access the course lecture video live, but they were only offered an email option for live feedback. Future course offerings were to experiment with dedicated audio links, but were not implemented. The original intent was to provide the live video at a rate conducive to home access (32–64 kbs). This rate was acceptable for the audio portion, but the video was significantly broken up, and the instructor's slightest movement looked like an instantaneous jump. Subsequently the streaming rate was increased to ISDN (note this course was taught before broadband access was widely available).

One of the authors of this paper (T. Edgar) taught an undergraduate process control course in Spring, 2005, to two University of Michigan students, who co-enrolled with 60 other students at UT-Austin. From the instructor/TA perspective, two additional students did not add a disproportionate amount of additional work. While the students did not attend class, they had access to the Seborg et al. (2004) textbook and extensive power point slides used in the class (www.che.utexas.edu/course/che360). The students submitted all homework assignments electronically, while exams were sent to a U. Michigan professor, who proctored the exams and mailed the exam papers back to the professor at UT-Austin. Several conference calls with the students were held during the semester and regular emailing between students and professor/TA handled content and homework questions. Clearly these two students were highly motivated, and they needed this course to graduate in June (process control is not taught in the spring semester at U. Michigan, just in the fall). Both students plan study beyond the B.S.Ch.E. level; one earned an A and the other a B. Enrollment was handled through the UT-Austin Extension Division, so university tuition numbers did not apply. The course fee was selected to be consistent with the equivalent tuition at U. Michigan for one course. One future enhancement would be to stream video of the actual class using an inexpensive camera to the students, who could review it at their leisure (not interactive). Communication with the instructor by cell phone during the class for questions would be another possibility.

Dan Rivera of Arizona State reports he allowed outside enrollment of one student from the University of Pittsburgh. He said, "I do agree that for these specialized courses the concept of collaborating among universities is a great idea, but is somewhat hampered by institutional requirements and restrictions. For example, I had one of Robert Parker's students take my system ID course a couple of years ago, and we had to be rather creative so that the course would be both affordable and the student could receive grade credit for his effort".

Other faculty have been asked about offering graduate courses outside their university. If the technology and enrollment bureaucracy issues could be worked out, some faculty would consider enrolling students from other universities to take their graduate control course in the future. It should be conducted in a technology classroom using streaming video in a videoconferencing mode, and the students could interact with the instructor through some audio link, including a cell phone. The downside of such a venture is the time investment to overcome the logistical and technological hurdles for the first few offerings. However, it might increase enrolment from the expected 10 or less to around 20.

Based on his experience Professor M. Kothare believes that basic level courses such as the introduction linear control class (state space, controllability, etc.) could certainly be taught jointly with other universities since the audience per year is typically small, i.e., between 5 and 10 students. Thus combining courses across virtual media (satellite, web, etc.) between universities in a rotating fashion would help in sharing the teaching load at graduate level. The same comment applies to a number of other courses at the advanced graduate level, e.g., nonlinear analysis and nonlinear dynamics. It is virtually impossible to provide a broad offering of courses in the systems area for control graduates with limited faculty time and joint courses would substantially enhance the graduate education.

One faculty member (J.B. Rawlings) suggested another reason, namely, sometimes faculty want to develop a specialized graduate course on a fast cycle in order to implement some new ideas, teaching materials, software, etc., but it cannot be done because local graduate enrollment does not justify it. By increasing potential enrollment, one can increase the frequency with which you can teach such courses. That can be very helpful, both for local students waiting to take the course, and the instructor waiting to try out some new ideas. Another benefit is that it allows students from other places to have access to resources (instructors, materials) that they cannot find locally. Such a non-traditional course has far-reaching and nonobvious consequences, not all of them good for the status quo in the local environment that might oppose such changes. But if a change clearly adds value, then the local policies should be changed to adjust to that new situation.

One distance education option that has been tried in a few fields is for faculty at two universities to team-teach a graduate course in two classrooms joined by a video link. In practice each faculty member would probably give fewer lectures than in a full course, which would make up for the additional work required to conduct the distance education version. In this case, students would enroll at their respective institutions, and each faculty would get credit for teaching one of the two courses, so no unusual tuition arrangements would be required. This idea could be extended informally to handle multiple graduate course exchanges between two or more universities, which is similar to the financial arrangement used by some universities to handle study abroad for their students (exchange student model). A department could get course "credits" for students who enroll from a cooperating university, then they could use those "credits" to have their students take courses at the other school. Students would enroll at their home university when taking courses using some general course number, which enables that university to collect the revenue locally. However, there is no tuition difference that has to be accounted for in this model.

5. Skills needed in systems Ph.D. graduates

5.1. Industry viewpoint

A limited poll of industry was conducted to identify desirable skills of Ph.D.'s in the systems area. In other words, how should graduate students in the systems area be prepared for positions in industry? The following list was distilled from six respondents in chemicals, software/consulting, and semiconductor companies:

- Capable of using mathematics, various software tools, good programming skills;
- Knowledgeable about advanced control technology (e.g., MPC);
- Able to convert data into information, decide on possible actions;
- Able to translate open-ended, complex, real-world problems into mathematical models;
- Understands quality of data and quality of models;

- Has good communication and relationship skills, able to lead projects, comfortable in a team environment, able to sell ideas through persuasion;
- Experienced with collaborative, multi-disciplinary projects;
- Able to work independently, assume responsibility for work, and complete tasks on-time;
- Able to work with clients, customers, end users, plant operators and managers;
- Willing to dive into new fields, new areas of knowledge;
- Has previous industrial experience (e.g., via internship or research project).

The above list is similar to the desirable attributes for B.S. chemical engineering graduates in the companion paper to this one on undergraduate process control education, although the above list implies a more technically sophisticated engineer.

The Molecular Frontiers report by the National Research Council (2003) stated a broad vision that future Ph.D. graduates in traditional and emerging industries should be able to understand the basic chemistry of traditional chemical processes, living systems, and advanced materials; synthesize and manufacture new substances with high selectivity for the desired product, low energy consumption, and benign environmental effects; design chemical processes that are safe, compact, flexible, energy efficient, environmentally benign, and conducive to the rapid commercialization of new products; understand and control how molecules react over different time scales and ranges of molecular size; develop new ways of energy generation, storage, and transportation to address sustainability; and work in an interdisciplinary team of scientists, engineers, and production personnel to bring new substances from the lab, to production, and then to market. While the above characteristics are more closely aligned with chemistry/chemical engineering graduates who specialize in areas outside of process systems, there is some overlap with the list of desirable attributes given earlier in this section.

The implementation and integration into industrial practice of the academic advances and contributions to the systems area are almost exclusively carried out by systems Ph.D. graduates working in industry. Recent examples of these technologies include state-space model predictive control, controller performance monitoring, and subspace system identification. From this perspective, an additional characteristic of future Ph.D. graduates is the ability to take a theoretical concept from the pages of a journal all the way to the control room. As chemical engineering expands its horizons into new, nontraditional fields, the systems area must also expand into these areas in order to provide exposure and competency to its graduates. A key factor used to judge the relevance of the systems area within chemical engineering will be the integration of systems technology into emerging nontraditional fields.

5.2. Future employment opportunities

Opportunities for Ph.D. students will likely track projected high growth areas over the next 10 years (see the Frontiers website at MIT (2006)):

- Solutions-to-the-customer;
- Integration of technological services, chemicals, materials;
- Information, electronics, telecommunications;
- Semiconductors (displays, inks, specialty polymers, energy devices);
- Medical (diagnostic, packaging, fabrics, surgical supplies);
- Safety, security, protection (diagnostic, protective materials);
- Materials/components for a cleaner, healthier environment (home, office) and personal care;
- Material components and energy devices (autos, planes).

It is clear that systems Ph.D.'s can apply their skills in many of these growth areas. Another trend in the future will be to make industrial companies more knowledge-intensive, which is to some extent driven by analysts in the financial markets. Certainly the quantitative skills in modeling and decision-making possessed by systems Ph.D.'s will be valuable in this new environment, although Ph.D. graduates will need to be adaptable to new problems and new industries, and be able to customize

Table 5
Employment distribution of Ph.D. graduates from selected departments (2000–2005)

	UT	UW	CMU	Purdue	UCSB/Delaware	Lehigh	Alberta	McMaster	DTU	AIChE (%)[a]
Government	1	–	2	1	–	2	–	–	–	–
Academic[b]	2	1	2	0	7	5	5	1	2	–
Chemical/fuels	3	2	12	9	–	4	3	7	2	47
Electronics	11	1	–	–	–	1	–	2	–	15
Food/consumer/auto	–	–	1	1	–	–	–	1	1	1
Materials	–	–	2	1	1	–	–	1	1	1
Biotech/pharma	0	1	–	–	2	–	–	2	5	18
Pulp & Paper	2	–	–	–	2	–	–	–	–	–
Engineering services	–	–	–	–	–	1	–	2	2	9
Software/consulting	3	–	1	4	4	2	4	3	2	4
Business services	–	1	1	2	–	–	–	–	–	5
Other (law)	1	–	–	–	–	–	–	–	–	1
Total	23	6	21	18	16	15	12	19	15	–

[a] Industrial employment (no academic/government placement data) for 2003 (AIChE).
[b] Does not include postdoctoral positions.

solutions to the customer. It is difficult to predict the timing of increased employment opportunities for Ph.D.'s in specific areas like biotechnology, nanotechnology, energy, advanced materials, electronics, and information technology. As a reference point, hiring trends from ten universities and data reported by AIChE shown in Table 5 indicate that systems Ph.D.'s still mostly accept employment in the traditional industrial sectors. The one department in Europe in the survey (DTU) has a strong showing in biotechnology hiring, due to the industry present in that region of Europe. This table is based on 5 years of data from major producers of chemical engineering Ph.D's in systems and control, mostly in the U.S. and Canada. Of the 145 Ph.D. graduates, 25 (17%) have taken academic positions, although mostly outside the U.S. There have been relatively very few systems faculty hires in U.S. chemical engineering departments since 1995. This is a trend that is unlikely to be reversed in the near future, so graduate control education should probably focus on the typical student who plans a career in industry.

6. Conclusions and recommendations

It is clear from the nearly 50 responses to the survey that a rich assortment of graduate courses in systems and control are offered by chemical engineering departments around the world. Two types of courses are offered, "integrated subjects" and "selected topics", with more of the former being offered. A wide range of textbooks is used in these courses with perhaps only the textbook by Skogestad and Postlethwaite (2005) standing out, in terms of frequency of usage. Most universities offer a broad range of supporting courses in control outside of chemical engineering in departments like electrical, mechanical, or aerospace engineering. This interdisciplinary flavor is certainly a strong feature of graduate control education, and makes students with this background attractive in the job market. A few departments offer laboratory experiences in their course offerings, but it is unclear if this is an important consideration in industrial hiring today (versus a student's experimental background as part of a Ph.D. project).

Simulation examples, case studies, and course projects are the norm in graduate control courses. Only a few schools use challenge problems developed by industry for academia (e.g., Tennessee Eastman, Shell fractionator). Clearly faculty like to put their specific creative imprint on the course they teach, although one has to wonder about the efficiency of such an approach, given time demands on faculty.

Because of the diversity of content at individual universities, it seems logical to share such information through a depository of web-based modules or a virtual textbook. An organizational meeting for such an effort was held at CPC7, due to the high level of interest stated in survey responses, both in using and in contributing to such educational modules.

Distance education in systems and control is carried out on a limited basis, with several success stories reported. There is interest in sharing specialized courses offered by experts around the world by using videoconferencing technology to link multiple classrooms together through the Internet. It will take several highly motivated "early adopters" to make this happen, even though the necessary hardware and software is commercially available today.

Industrial employment patterns for systems and control Ph.D.'s are still tilted towards the chemicals, fuels, semiconductor, and software sectors; not much employment in the emerging industries (e.g., biosystems) has occurred during the past 5 years in the U.S.A. and Canada, based on a survey of departments producing a large number of Ph.D.'s. Companies are looking for well-rounded individuals with a broad set of skills that go beyond the ability to develop new theory or algorithms, such as providing customer-focused solutions. Faculty should be concerned with giving their graduate students a broad set of experiences while they are in residence to prepare them for the industrial environment.

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