A GRADUATE COURSE IN DIGITAL COMPUTER PROCESS CONTROL

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Computer-based control systems have become a routine feature in the process industry. In order to be competitive, today's students must be familiar with the recent developments in control technologies which are having a significant impact on how complex industrial processes are operated. The first-listed author of this paper began offering a course in computer process control in 1975, based on the material in the literature[10,30] at that time and his own perspectives. In the ensuing years, however, the course has been completely revised in light of the new and significant developments in control technology.

This paper describes what we believe to be a modern course in digital computer process control. Whenever appropriate, recent developments are highlighted, and a detailed bibliography of the textbooks and selected papers used in the course is included at the end of the article for ready reference.

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The goals of the course are to learn how to design, analyze, and implement direct-digital control systems for single-loop and multivariable systems.

THE REVISED COURSE

An outline of the revised course in shown in Table 1. For convenience, the course is divided into three parts: Part 1 is devoted to introductory concepts and the development of a mathematical background; Part 2 covers the analysis and design concepts of SISO digital control systems; and Part 3 is concerned with advanced control concepts.

PART 1
Introductory Concepts and Mathematical Background

The course begins with an introduction to digital computer control. The essential features of conventional control based on continuous or analog signals and of digital control, which encompasses hybrid (discrete/analog) signals, are outlined. The meanings of direct-digital control (DDC), supervisory control, and distributed control are explained.

Much of the material in the course deals with DDC concepts, and as a lead-in to the next series of topics, the elements of a single-loop DDC system are examined. We point out that the DDC-loop consists of the usual elements of any control system—namely, the process, a measurement-device transmitter, and a final control element. In addition, a DDC system has an analog-to-digital (A/D) converter that samples measured process outputs at a sampling frequency selected by a real-time programmable clock, a digital computer or digital controller, and a digital-to-analog (D/A) converter that converts computer-generated discrete control commands into continuous signals for operating the final control elements.

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The goals of the course are to learn how to design, analyze, and implement direct-digital control systems for single-loop and multivariable systems. It should be emphasized that the availability of control computers allows the designer to implement control methodologies that are either impractical or impossible with conventional control hardware. Examples include dead-time compensation, feedforward control, synthesized digital control algorithms, and model predictive control.

The sequence of lectures is devoted to the study of each element of the DDC loop. The first among them is concerned with computer-control hardware and software. The hardware description includes the central processing unit, the main memory/bulk memory, the computer input/output (I/O) devices, process I/O, the A/D and D/A converters, and a real-time programmable clock. The software concepts include an introduction to assembly-level programming, real-time Fortran, and Basic. At the University of Louisville a PDP 11/03-system has served our control-computing needs for the last several years. The Fortran callable subroutines for A/D, D/A, and the real-time clock for this machine are used to explain how the real-time commands are embedded into a Fortran control program.

TABLE 1
Syllabus: Digital Computer Process Control Course

Topic #	Description	Time Devoted (50-min. periods)	References
	PART 1: Introductory Concepts and Mathematical Background		
1	Introduction to computer process control	1	7, 21, 23
2	Computer-control hardware and software	3	7, 9, 20
3	How to implement PID controllers with digital computers	2	7
4	Mathematical representation of A/D converter	1	7
5	z-transforms	4	7, 12, 21, 23
6	Transfer function of D/A converter	1	7, 25
7	Pulse transfer functions	1	25, 11, 7
	PART 2: Analysis and Design of Digital Control Systems		
8	Open-loop response, impulse-response models, closed-loop responses	3	25, 11, 7
9	Design of digital-control algorithms; deadbeat-control Dahlin algorithm; internal-model control (factorization method); Smith predictor; simplified-model predictive control; conservative-model based control; PID control	6	7, 8, 12, 26, 37, 21
10	Stability of sampled-data control systems	1	7, 25
	PART 3: Advanced Control Concepts		
11	Process identification; step testing; pulse testing; dynamic matrix identification; introduction to time-series analysis	5	12, 7, 6, 36
12	Practical nonlinear control	2	32, 50, 30, 31
13	Adaptive control and self-tuning; auto-tuning; gain scheduling; model reference adaptive control; self-tuning regulators	2	28, 2, 59, 61,7
14	Feedforward control	1	7, 12, 21
15	Cascade control	2	7,12
16	Multivariable control	7	7, 8, 12, 46, 53, 17, 18, 40, 41
	TOTAL	**42**	**periods: one semester or equivalent**

The next topic deals with single-loop PID control. In typical industrial situations, fast loops (flow loops) operate under digital PID-type control algorithms. In these lectures the instructor derives the digital PID algorithm from conventional controller equations that the students are familiar with and points out the role of the sampling period in stability and performance. At the end of the lectures the students develop a computer program and implement digital PID control on a four-loop laboratory process.[10] (Note that doing this work does not require a background in z-transforms.) Being able to operate a process under the control of a digital computer after only three weeks of the semester has been an exciting experience for the students.

The next topics to be covered are mathematical representation of an A/D converter, study of z-transforms, derivation of a pulse-transfer function, and the zero order hold transfer function. Then open-loop and closed-loop pulse transfer functions are derived, and open-loop and closed-loop responses are evaluated by hand and the answers verified by CAI (Computer-Aided Instruction) software that has only recently been developed. Information on this CAI-control software can be found in the references at the end of this article.

PART 2
Design and Analysis of Digital-Control Systems

The discussion of pulse-transfer functions and open-loop responses leads us into an exciting topic—the notion of an impulse response (IR) model, which enables us to predict the process output at the next sampling instant from past inputs through use of the equation

$$Y_{K+1} = \sum_{i=1}^{N} h_i \, u_{K+1-i} \qquad (1)$$

Beginning with the definition of the pulse-transfer function, $G(z) = Y(z)/U(z)$, the instructor can easily derive Eq. (1), as shown for example in Deshpande and Ash.[7] IR-type models have distinct advantages: they can be derived from easily-available step response data; the response curve need not be fitted to a structured model and the order of the process is not important; and the use of an IR-type model considerably simplifies the evaluation of closed-loop responses by computer simulations.

The next topic is the design of digital-control algorithms for SISO (Single-Input Single-Output) systems. While controllers can be designed by a number of methods, we believe that the direct-synthesis method is best suited for this course. The basic idea is to solve the closed-loop pulse-transfer-function equation for the controller, giving

$$D = \frac{Y/R}{1 - Y/R}\frac{1}{\tilde{G}} \tag{2}$$

The closed-loop response is specified according to the equation

$$\frac{Y}{R} = FG_{+} \tag{3}$$

By selecting the desired expressions for F, several well-known control algorithms can be obtained; for example, the choice of $F = 1$ gives deadbeat control. Through use of the CAI software, students quickly learn that deadbeat control can give rise to rippling behavior of the controller output. Furthermore, deadbeat controllers are very sensitive to modeling errors.

The choice of a first-order lag for F gives a Dahlin algorithm. The instructor can easily show that a Dahlin algorithm is the same as an internal-model-control (IMC) algorithm if a first-order filter is employed in the latter. It would also be helpful to derive the IMC structure from the sampled-data control structure and show that the two representations are equivalent. Once the IMC structure is derived, one can go over the stability theorems and design IMC controllers for a variety of processes—including those that exhibit dead-time and inverse response.

In the discussion of IMC, the instructor can derive the Smith Predictor algorithm and point out the similarities between the two approaches. Also, through simulation exercises, the instructor can show that the latter does not tolerate modeling errors well and that the tuning of the Smith Predictor-based PID controllers becomes difficult in the presence of modeling errors.

At one end of the spectrum of control equality there is a notion of perfect control (deadbeat control). IMC is an algorithm that delivers perfect control in the absence of modeling errors. In the presence of modeling errors, however, the designer must back away from the notion of perfect control in favor of robustness, by choosing an appropriate filter.

At the other end of the spectrum of control quality there is the notion of open-loop control. Simplified model-predictive control (SMPC) and conservative model-based control (CMBC) are algorithms which assume that at worst the controller should be able to provide a set-point response that is as good as the open-loop response. These algorithms are derived as follows: the open-loop behavior of an open-loop stable process is given by

$$\frac{Y}{R} = \frac{1}{K_p}\tilde{G} \tag{4}$$

Substituting for Y/R from Eq. (4) into Eq. (2) gives

$$D = \frac{M}{E} = \frac{1}{K_p - \tilde{G}} \tag{5}$$

The choice of Eq. (5) for the controller will deliver a set-point response that is the same as the normalized open-loop response. The response can be speeded up by introducing a tuning-constant α, giving the SMPC algorithm

$$D = \frac{\alpha K_p}{K_p - \tilde{G}} \tag{6}$$

SMPC features a single-tuning constant that can be found by offline optimization. Dead-time compensation can be incorporated by modifying Eq. (5) according to

$$D = \frac{A}{K_p - A\tilde{G}} \tag{7}$$

where

$$A = \frac{1 - \beta z^{-1}}{1 - \beta} \tag{8}$$

Equation (7) represents the CMBC control law. CMBC also features a single-tuning constant β whose value can be found by offline simulation.

In the discussion of various control algorithms, the students are reminded that the algorithms which give the best servo responses are not necessarily the ones that are best for regulatory control. Furthermore, the design work assumes that the processes are linear, but in reality they are not. Consequently, the algorithms that give the best performance in simulation work may not be the best when they are implemented on real-life nonlinear processes.

The next topic of discussion is stability. Stability concepts relating to sampled-data systems can be effectively derived by utilizing the relationship between the Laplace transform operator s and the z-transform operator z. The discussion of stability concludes with a method for finding the roots of the characteristic equation in the z-domain.

PART 3

Advanced Control Concepts

The next topic is process identification. The traditional methods which we cover are step testing, pulse testing, and fitting of models to frequency-response plots. An ideal method should identify process dynamics from a test that does not force the process away from the steady-state operating condition. One such method that meets these needs is the relay method in which a relay perturbs the process and the resulting process output/input data provide the ultimate frequency and ultimate gain of the system. These data lead to optimized tuning constants of a PID-type controller.

Another method, called dynamic matrix identification, calls for perturbing the process by a series of up-and-down step changes in the input U(z) around the steady state, given by the equation

$$U(z) = U_0 + U_1 z^{-1} + U_2 z^{-2} + U_3 z^{-3} \tag{9}$$

Then, in the light of the impulse response model

$$\frac{Y(z)}{U(z)} = \sum_{i=1}^{N} h_i z^{-i} \tag{10}$$

the output is given by

$$Y(z) = 0 + h_1 U_0 z^{-1} + \left(h_2 U_0 + h_1 U_1\right) z^{-2} + \ldots \tag{11a}$$

$$= 0 + Y_1 z^{-1} + Y_2 z^{-2} + \ldots \tag{11b}$$

Equations (11a) and (11b) show that the impulse response coefficients can be computed from the experimental input and output data.

The last method covered which is suited to use in a noisy environment is time-series analysis. In this method the process is described in two parts: one accounts for the model and the other is a noise term that accomodates the effect of unmeasured load disturbances. A PRBS (pseudo random binary sequence) signal is applied to the process and the analysis of the input-output data gives the model. Time constraints prevent an in-depth treatment of the theory, but the software available (*e.g.,* Matlab: see also Reference 21) can be effectively used to illustrate the method.

The next topic is practical nonlinear control. The treatment is restricted to a conceptually simple practical method which appears to have considerable potential. It is well known that the closed-loop response of many complex nonlinear SISO systems can be described by a linear second-order transfer function, given by

$$\frac{Y(s)}{R(s)} = \frac{\eta_1 s + \eta_2}{s^2 + \eta_1 s + \eta_2} \tag{12}$$

or, in the time domain

$$\left.\frac{dY}{dt}\right| = \eta_1 E + \eta_2 \int E\,dt \tag{13}$$

where E = R - Y.

The terms η_1 and η_2 determine the shape of the response. Now, the nonlinear process is described by a nonlinear differential equation of the form

$$\frac{dY}{dt} = f\left(Y^n,\ \ell n\,Y,\ e^{AY},\ \text{etc.}\right) + U \tag{14}$$

Equating Eqs. (13) and (14) gives the nonlinear control law

$$U = -f\left(Y^n, \ell n\,Y, e^{AY}, \text{etc.}\right) + \eta_1 E + \eta_2 \int E\,dt \tag{15}$$

If the resulting control law turns out to have undesirable properties, such as ringing or constraint violations, then a minimization problem based on the difference between actual and the desired values of the derivative dY/dt is solved to derive the control law. Note that this analysis of nonlinear control is based on continuous-time systems. The system equations would have to be discretized for use in a digital-computer-based control system.

The next set of topics falls into the category of what is commonly referred to as advanced control concepts. The first topic to be covered is adaptive control and self-tuning. Time limitations permit only a brief introduction. The need for adaptive control arises due to changing process characteristics. Auto-tuning, gain scheduling, self-tuning regulators, and model-reference adaptive control are examples to be covered. The use of a relay to identify the ultimate gain and ultimate period of a proportional controller in auto-tuning has already been mentioned.

Feedforward and cascade control are the next topics to be covered. Feedforward control is meant to improve the response of feedback control systems in the presence of disturbances in process loads, while cascade control is meant to arrest the detrimental effect of disturbances in the manipulated variable.

The final topic to be covered deals with multivariable control, which includes the topics of interaction analysis and variable pairing, multiloop control for modestly-interacting systems (including PID controllers designed by the biggest log modulus tuning method), multiloop IMC and CMBC/SMPC controllers, explicit decoupling in conjunction with PID controllers, reference systems decoupling, and multivariable model predictive control. Model predictive control includes dynamic matrix control, model algorithmic control, and predictive IMC.

Model predictive control techniques utilize step- or impulse-response models of the process. These models are used in conjunction with optimization techniques to calculate controller outputs. It should be emphasized that complex multivariable processes must invariably be operated in the vicinity of constraints. Therefore, students must have familiarity with some methods, such as linear and quadratic programming for solving constrained multivariable optimization problems and how they are used in conjunction with model predictive control. Simulation examples can be used to illustrate the concepts.

This concludes the course. The first-listed author offers the course regularly at the University of Louisville and as an intensive short course for industry in the U.S., Europe, Kuwait, and India. The reactions of the participants have always been favorable.

NOMENCLATURE

D = digital controller
E = error
F = filter
= model transfer function
G_+ = nonminimum phase element
h = impulse response coefficient
i = sampling instant
K_p = process steady-state gain
M = controller output
N = number of sampling periods in open-loop settling time
R = set-point
s = Laplace transform operator
t = time
U = process input
Y = process output
z = transform operator

Greek

η_1,η_2 = PID-type tuning constants
α,β = tuning constants

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ChE ***letter to the editor***

THE ACADEMIC ELITE IN CHE

Dear Editor:

A ranking of the most highly regarded doctoral programs in chemical engineering was presented in the November 1983 edition of *Changing Times.*[1] This ranking was based on a study published by the National Academy of Sciences.[2] For the ranking reported by *Changing Times* two key measures of reputation from the National Academy study were combined: 1) "faculty quality" assessed how chemical engineering professors around the country rated their peers in the same discipline, and 2) "program quality" assessed how well the faculty thought each program educated research scholars and scientists. *Changing Times* combined these two measures and derived a ranking of the top ten percent of the programs in chemical engineering. If one goes by the assumptions of the *Changing Times* article, the eight schools with the highest combined scores represented the "academic elite" in chemical engineering—the "best" programs in the country.

Given the subjective nature of the evaluation process which produced the National Academy ratings, I decided to examine the composition of the faculties of the top eight schools. I suspected that these departments would be substantially linked to one another through the hiring of one another's graduates, hence enhancing one another's reputations. I also expected that among the academic elite there would be a high degree of academic "inbreeding"—the hiring of graduates from one's own program.[3]

I used the *American Chemical Society Directory of Graduate Research 1989* to examine the full-time faculties of the eight highest-ranked chemical engineering departments. An item of primary interest was where the full-time faculty members at these institutions had received their doctoral degrees. It