THE INTEGRATION OF REAL-TIME COMPUTING INTO PROCESS CONTROL TEACHING

PART II: THE UNDERGRADUATE COURSE*

M. MORARI and W. H. RAY
University of Wisconsin
Madison, Wisconsin 53706

PROCESS CONTROL FOR undergraduates is offered each semester and has enrollments of 30 to 50 students. The course has two lecture periods, one recitation period, and one 3 hour laboratory period each week. The curriculum (shown in Tables 1 and 2) has been selected to give the student a balanced mixture of useful theory and hands-on practical experience in process dynamics, measurement, and control.

COURSE DESCRIPTION

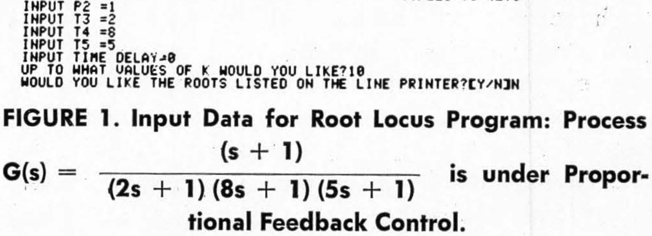
THE INSTALLATION OF A PDP11/55 minicomputer system described in Part I of this article has allowed a complete restructuring of the course material. A large library of computer programs for the design of control systems is available and is still growing. The use of these programs makes it possible to design control systems for meaningful practical processes without the drudgery of laborious hand calculations. Thus, course time is freed and it becomes possible to cover topics generally neglected in undergraduate courses, e.g. multivariable control. The lecture material is listed in Table 1 and includes considerations of how to choose loop pairings, how to minimize interactions between control loops and how to tune multivariable systems. In the latter part of the semester a number of graphical interactive computer aided design programs are used for detailed case studies. The present library includes routines for the generation of Bode plots, root loci and

TABLE 1
Undergraduate Process Control Lecture Topics

1. **Review of Laplace transforms and matrix algebra**
2. **Principles of real-time computation and data acquisition**
3. **Transient and frequency response of linear systems**
4. **Feedback control of linear systems**
5. **Stability of linear systems**
6. **Control system design for linear systems**
7. **Nonlinear systems**
8. **Case studies**

TABLE 2
Undergraduate Process Control Laboratory Experiments

1. **Techniques of analog simulation**
2. **Techniques of digital simulation**
3. **Dynamics of interconnected water tanks**
4. **Computer aided data acquisition**
5. **Frequency response and process identification through pulse testing**
6. **Calibration and dynamic response of PID controllers**
7. **Feed forward, feedback, and cascade control**
8. **Multivariable control of a gas distribution system**
9. **Multivariable control of a multi-sidestream distillation column**
10. **Tuning of a level controller with strong system nonlinearities**



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        DESIGN MODEL

 1) G(S)=C*(P1*S+1)(P2*S+1)/(T3*S+1)(T4*S+1)(T5*S+1)

 OR

 2) G(S)=[A(1)+A(2)*S+....A(N)*S**(N-1)]/[B(1)+B(2)*S+....B(M)*S**(M-1)]

    GC(S) = K*(1 + TD*S + 1/TI*S)

 WHICH WOULD YOU LIKE[1 OR 2]?1                   CONTROLLER
 INPUT C = 1                                      1) P  2) PD  3) PI  4) PID
 INPUT P1 =0                                      TYPE[1 TO 4]?1
 INPUT P2 =1
 INPUT T3 =2
 INPUT T4 =8
 INPUT T5 =5
 INPUT TIME DELAY=0
 UP TO WHAT VALUES OF K WOULD YOU LIKE?10
 WOULD YOU LIKE THE ROOTS LISTED ON THE LINE PRINTER?[Y/N]N
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FIGURE 1. Input Data for Root Locus Program: Process $G(s) = \frac{(s+1)}{(2s+1)(8s+1)(5s+1)}$ **is under Proportional Feedback Control.**

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*Part I dealing with graduate education in process control appeared in the Fall 1979 issue of *CEE*.

Nyquist diagrams for open loop, closed loop and cascade control systems. In addition, a number of programs for the design of multivariable systems are presently available. Output from these programs usually appears as plots drawn on the screens of graphic terminals, and paper copies (to be included in student reports) are obtained by the student at the push of a button. Example: if a root locus diagram is to be drawn the user would be asked to specify the transfer function parameters and other variables as shown in Fig. 1. Upon completion of the questions a diagram (as in Fig. 2) will appear which can be subsequently enlarged or otherwise modified.

The laboratory, which is designed to complement the lecture material, is comprised of some ten experiments (cf Table 2). Most of these experiments are carried out by each laboratory group in the course of the semester. Many experiments involve real time computation and are selected to familiarize the students with the modern methods of implementing control algorithms. These presently include:

- **Data acquisition (noise suppression, signal amplification, A/D conversion, sensor calibration, etc.)**
- **Pulse testing (data acquisition, input pulse selection, Fourier transformation of data, frequency spectrum analysis, frequency response parameter determination, etc.)**
- **Multivariable feedback control of interconnected gas storage tanks (process modelling, data acquisition, single loop PI control, supervisory computer control, direct digital control, etc.)**
- **Multivariable feedback control of a multi-side-stream distillation column (process modelling, data acquisition, single loop control, supervisory computer control, and direct digital control)**

Let us discuss two of these experiments in more detail.

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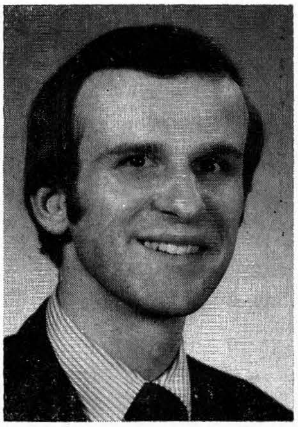
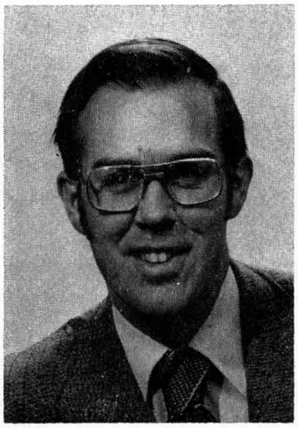


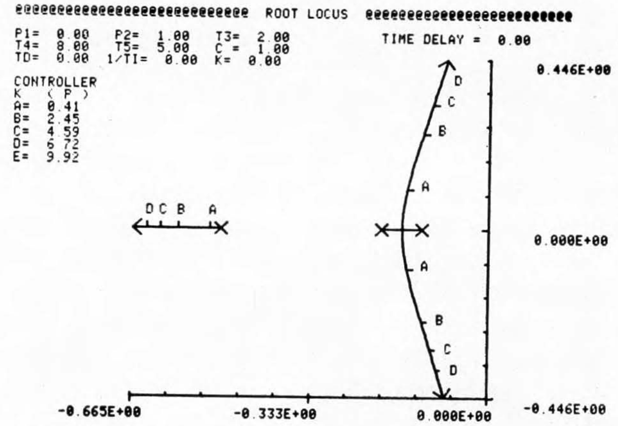


Manfred Morari was born in Graz, Austria on May 13, 1951. He obtained his undergraduate education in chemical engineering at the Swiss Federal Institute of Technology (ETH), Zurich. After his diploma he started graduate school at the University of Minnesota in 1975. Upon completion of his doctorate he joined the ChE faculty at the University of Wisconsin in 1977 where he is currently assistant professor. Last summer he worked for Exxon Research and Engineering Company. His research interests include a variety of topics from the areas of process synthesis and process control: synthesis of separation sequences, optimal measurement selection and inferential control, optimizing control and the dynamics and control of large integrated processing systems. **(L)**

W. Harmon Ray was born in Washington, D.C., on April 4, 1940. He received the B.A. and B.S. Ch.E. degrees from Rice University, Houston, Texas, in 1962 and 1963 respectively, and the Ph.D. degree in ChE from the University of Minnesota in 1966. He has been on the faculty of the University of Waterloo in Canada (1966-70), the State University of New York at Buffalo (1970-76), and the University of Wisconsin, Madison, where he is presently Professor of ChE. During the 1973-74 academic year, he was on sabbatical leave as a Guggenheim Fellow in Belgium and Germany. His research interests include chemical reactor engineering and process modelling, optimization, and control. His publications include an edited volume "Distributed Parameter Systems" (Dekker, 1977), and two monographs "Process Optimization" (Wiley, 1973) and "Advanced Process Control" to be published by McGraw-Hill in 1980. **(R)**

Pulse Testing

THIS EXPERIMENT CONSISTS of putting a measured pulse of hot water into a stirred mixing tank having continuous inflow and outflow. Input and output temperatures are measured under computer control and the resulting data analyzed to provide frequency response information-



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@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@ ROOT LOCUS @@@@@@@@@@@@@@@@@@@@@@@@@@@
P1=  0.00   P2=  1.00   T3=  2.00              TIME DELAY =  0.00
T4=  8.00   T5=  5.00   C =  1.00
TD=  0.00 1/TI=  0.00   K=  0.00

CONTROLLER
K    ( P )
A=  0.41
B=  2.45
C=  4.59
D=  6.72
E=  9.92
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FIGURE 2. Root Locus Diagram for the Feedback Control Loop in Figure 1.

tion and parameters for a process model (i.e., a gain and time constant for this simple first order process). Typical results, taken from a student lab report, are shown in Figures 3 and 4. The measured input and output temperatures are shown in Figures 3 while the resulting Bode plot showing the frequency response may be seen in Figure 4. The process gain of 1.0 is readily found from the low frequency asymptote of the amplitude ratio (AR). By using both amplitude ratio (AR) and phase angle (ϕ) to estimate the corner frequency, ω_c, two separate estimates of the tank time constant are found. Usually these are in reasonable agreement with the "theoretical" value determined from the mean residence time of the tank.

Multivariable Control of Interacting Gas Storage Tanks

One of the most sophisticated experiments carried out by the students is the modelling and multivariable feedback control of a pair of interacting gas storage tanks. This experiment requires three laboratory periods plus some lecture preparation. The purpose of this experiment is to demonstrate to the student the effects of interactions in multivariable systems and to give him or her the possibility of testing different multivariable control schemes on a real system.

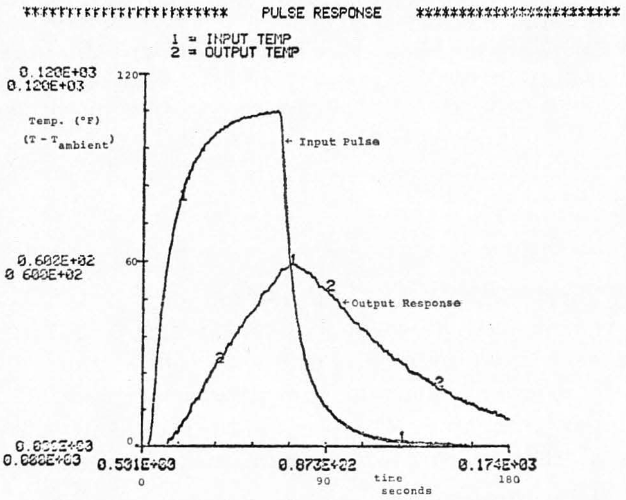

FIGURE 3. Pulse Test Data for Mixing Tank.

A simplified version of the system flow sheet is given in Figure 5. Air enters the system at a constant pressure of 60 psig, flows through a control valve into the first tank and from there through another control valve into the second tank. Finally, the air passes through a fixed orifice, a rotameter, and is vented. The equipment is fully instrumented with two pressure gauges, pressure transducers, PI analog controllers and is also interfaced with the minicomputer allowing data acquisition, supervisory and direct digital control.

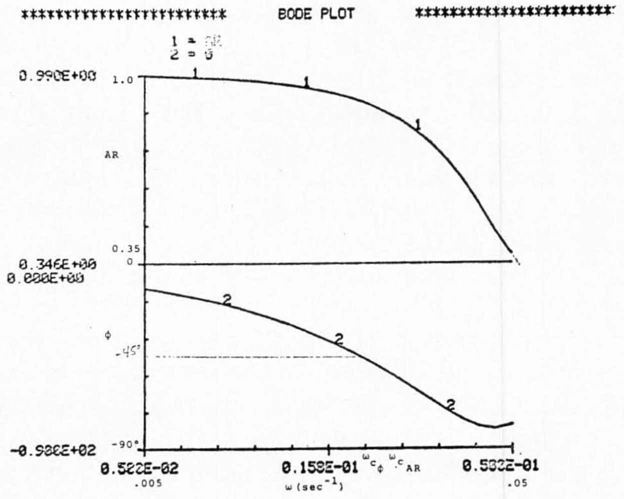

FIGURE 4. Frequency Response Bode Plot for Mixing Tank.

The first task given the students is to develop a mathematical model for the tank system. An unsteady state mass balance for each of the two tanks yields

$$\frac{dp_1}{dt} = \frac{RT}{V_1M}[C_{d1}A_1\phi(p_0,p_1) - C_{d2}A_2\phi(p_1,p_2)] \quad (1)$$

$$\frac{dp_2}{dt} = \frac{RT}{V_2M}[C_{d2}A_2\phi(p_1,p_2) - C_{d3}A_3\phi(p_2,p_3)] \quad (2)$$

where
R = universal gas constant
T = absolute temperature
V_i = volume of tank i
M = mean molecular mass of air stream
C_{di} = discharge coefficient for orifice i
A_i = area of orifice i

$$\phi(p_i,p_{i+1}) = \begin{cases} K_1\,(p_i(p_i - p_{i+1}))^{1/2} & p_{i+1}/p_i > .5 \quad (3) \\ K_2p_i & p_{i+1}/p_i < .5 \quad (4) \end{cases}$$

K_1, K_2 = material constants

All parameters of the model are available to

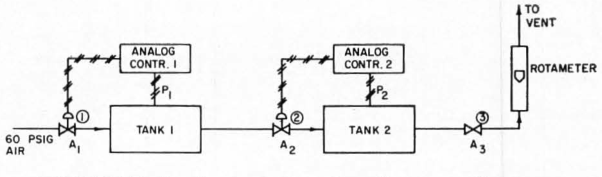

FIGURE 5. An Interacting Gas Storage System.

the student in tabulated form except the discharge coefficients which have to be determined through steady state experiments.

Computer control experiments are carried out with the goal of achieving a given gas production rate while meeting certain pressure constraints in the two gas storage tanks. Both Supervisory Control and Direct Digital Control algorithms are tested by the student. Different control objectives can be selected by the student but they all result in the regulation of the two pressures through changes in the two control valves. Let us briefly indicate some of the choices available to the student.

A. Supervisory control:

Possible control objectives:

1) **specified gas flow rate from tank 2 and**
2) **p_1/p_2 fixed or p_1 minimized or p_1 maximized**

In supervisory mode, the valves are under local analog control. After a control option is entered by the student via the computer terminal, the set points are computed and transmitted by the computer to the local controllers. The response to changes in objectives is observed for different flow regimes. (Critical or subcritical flow through the valves.) Set point compensation is attempted to yield a smoother servo behavior.

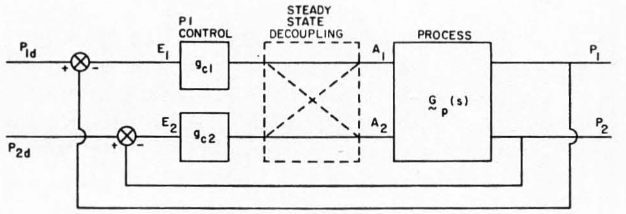

FIGURE 6. Control Structure for DDC Control with Single Loop PI Controllers and with Added Steady State Decoupling (dashed lines).

B. Direct digital control (DDC):

The possible control objectives are identical to those listed in part A. Different multivariable control algorithms are developed by the students and supplied to the main control program in the form of Fortran subroutines. As an example, steady state decoupling is implemented and compared with the usual single loop PI control. The controller structure is seen in Figure 6. The results of one laboratory group are shown in Figures 7, 8. With simple PI control, significant oscillations in the pressure response were found (cf. Figure 7). However, with the addition of steady state decoupling, the response was much improved (Figure 8).

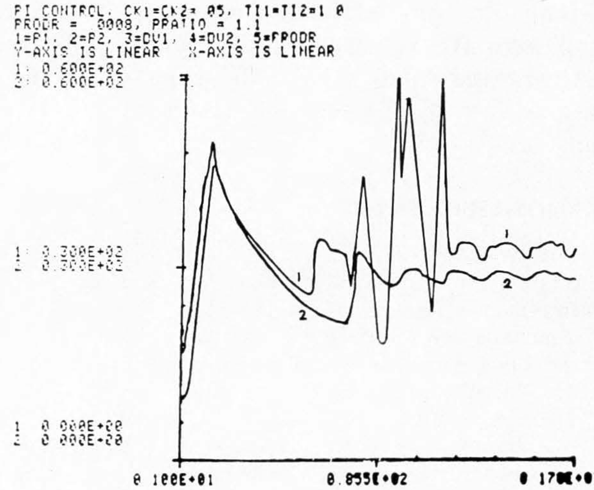

FIGURE 7. Process Response Under DDC With Single Input-Single Output PI Control.

CONCLUSIONS

THE NEW MINICOMPUTER has become an integral part of the undergraduate control course at Wisconsin. Aspects of digital computer control are demonstrated to the students and they have the opportunity to gain some practical experience with the implementation and application of modern control algorithms. Computer aided control

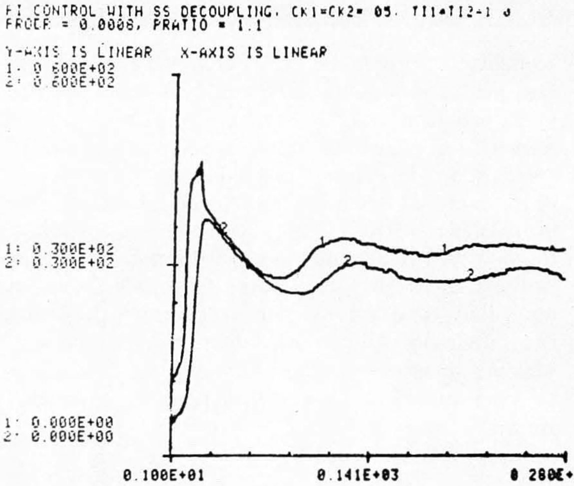

FIGURE 8. Process Response Under DDC With Steady State Decoupling and PI Control.

system design methods utilizing interactive graphics have replaced classic pencil and paper methods and have thus made time available to include new theoretical material in the curriculum. □

ACKNOWLEDGMENTS

Our progress in bringing real time computing into the process control curriculum at Wisconsin is due to the cooperative efforts of many individuals:

1. Emeritus Professor R. J. Altpeter, who originally established process control as a discipline at Wisconsin. He laid the foundation upon which the present curriculum is built.
2. Visiting Professor Ram Lavie, who shared his experience in the development of laboratory experiments.
3. The students who contributed their time and talents to the development of new experiments and computer aided design programs—these include Dennis Arnon, Dean Berceau, John Bolling, John Greiner, Tim Heisel, Sunny Lo, Bob Lojek, Diana Meseck, David Roark, John Seymour, and Pat Vilbrandt.
4. The technical staff and faculty of the department of Chemical Engineering who should be recognized for the support they have given this endeavor. In particular, the efforts of Mike Lynch, Todd Ninman, Jim Wenz and Don Zentner have been invaluable.
5. The more than 200 undergraduate and graduate students who have "consumer tested" the changes in curriculum and provided useful feedback.

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