EXPERIENCES WITH AN EXPERIMENTAL PROJECT IN A GRADUATE CONTROL COURSE

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A graduate-level class on process control traditionally employs a standard lecture-style course, possibly coupled with an independent course project carried out in a simulation environment. If one steps back to critique this approach, it is important to first address the skills required by a practicing process-systems engineer. As a guide to the requisite abilities required of a process-systems engineer, one may consult the list of control design steps provided by Skogestad and Postlethwaite[1] shown in Table 1. Is the typical engineering graduate well prepared to accomplish these tasks? There have been no comprehensive studies to answer this question, but Kheir, *et al.*,[2] reported the results of an informal survey of industrial employers of control engineers. The highest rated aspects of the current methods of control education were control-system knowledge, job preparation, and curriculum. The analytical skills of the students were considered strong. Such responses seem to indicate some success for items 7 through 9 of Skogestad's list of control-design steps, areas that correspond to skills typically emphasized by a theoretical, textbook-and-lecture control course.

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Unfortunately, existing approaches to control engineering education are not necessarily producing engineers who are as knowledgeable in other areas. The Kheir survey respondents reported that control engineers received lower ratings in the areas of laboratories, hands-on experience, and interpersonal skills. The course described in this paper uses both a standard lecture class and an experimental group project related to the course material. This provides an opportunity to address the deficiencies identified by Kheir and colleagues, while reinforcing the positive aspects of traditional control engineering education methods.

COURSE DESCRIPTION

In the latest (fall, 1998) offering of this course, Advanced Process Control, there were seven students enrolled for a grade and five students auditing the class. Of the seven students taking the class for a grade, five were University of Delaware graduate students and two were industrial professionals enrolled for continuing education credit.

As a main reference, the course used the text by Skogestad and Postlethwaite,[1] and the major topics covered in the course included

- Classical multivariable control
- Analysis of performance limitations
- Uncertainty characterization
- Robust controller synthesis
- Control structure selection and plant-wide control

One of the key strengths of the Skogestad and Postlethwaite text is the treatment of performance limitations, and this topic was covered in depth in the lecture and reinforced via the experimental project. The course project was assigned in the middle of the semester, and the students were given the choice of a theoretical independent course project (related to their thesis research) or the opportunity to work on the experimental system as a group project. Of the five on-site students, four elected to carry out their project using the experimental four-tank system.

EXPERIMENTAL SYSTEM

An interacting four-tank process is currently used in both the elective multidisciplinary undergraduate control laboratory and the advanced graduate control course. The design is inspired by the benchtop apparatus described in Johansson and Nunes.[3] A simple schematic is shown in Figure 1. Two voltage-controlled pumps are used to pump water from a basin into four overhead tanks. The two upper tanks drain freely into the two lower tanks, and the two bottom tanks drain freely into the reservoir basin. The liquid levels in the bottom two tanks are directly measured with pressure transducers, and the top tanks have high-level alarm signals generated by electro-optical sensors. As can be seen from the schematic, the piping system is configured such that each pump affects the liquid levels of both measured tanks. A portion of the flow from one pump flows directly into one of the lower-level tanks where the level is monitored. The rest of the flow from a single pump is diverted into an overhead tank, which drains into the other monitored tank. By adjusting the bypass valves on the system, the amount of interaction between the two pump flowrates (inputs) and the two lower tank level heights (outputs) can be varied. For this work, it is assumed that an external unmeasured disturbance flow may also be present that drains or fills the top tanks.

The original work of Johansson and Nunes[3] employed tanks with a volume of 0.5L. The present work uses 19L (5 gallon) tanks, attempting to create a visual impression of practical reality for the students. The scale of the apparatus is indicated in Figure 2. In the lower right-hand corner of the photograph, one can see the display of a computer control system used as an interface to the experiment. A Bailey Freelance Distributed Control System (DCS) was employed to introduce the students to actual operating software employed in industry. Furthermore, the PC-based architecture made the system cost-effective for a university application and facilitates hardware and software upgrade paths.

The experimental package consists of three sepa-

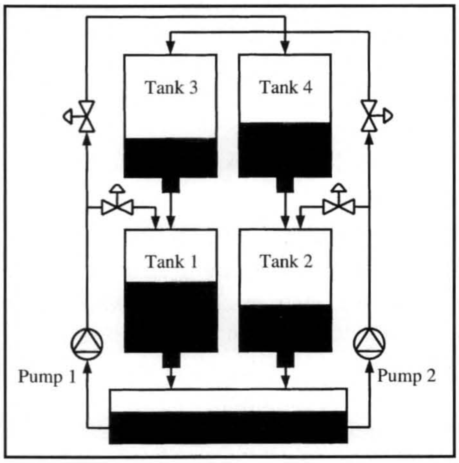

Figure 1. *Schematic of the four-tank system.*

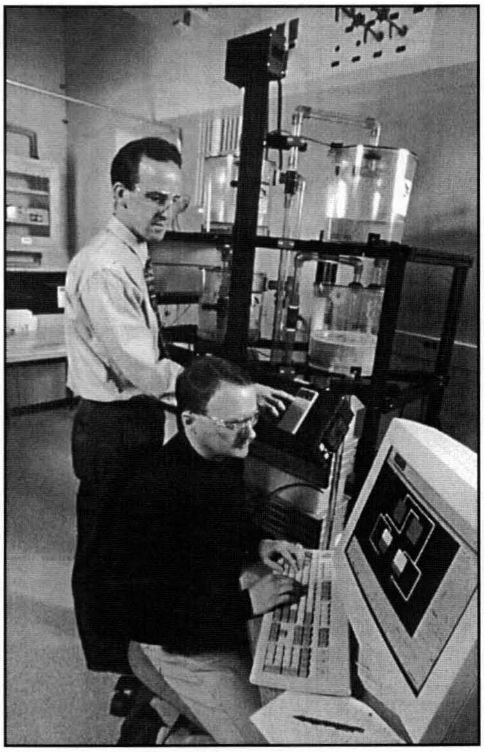

Figure 2. *Laboratory apparatus.*

TABLE 1
Steps in Control System Design

1. Study the system (plant) to be controlled and obtain initial information about the control objectives.
2. Model the system and simplify the model, if necessary.
3. Analyze the resulting model; determine its properties.
4. Decide which variables are to be controlled (controlled outputs).
5. Select the control configuration.
6. Decide on the type of controller to be used.
7. Decide on performance specifications, based on the overall control objectives.
8. Design a controller.
9. Analyze the resulting controlled system to see if the specifications are satisfied; and if they are not satisfied, modify the specifications or the type of controller.
10. Simulate the resulting controlled system, either on a computer or pilot plant.
11. Repeat from step 2, if necessary.
12. Choose hardware and software, and implement the controller.
13. Test and validate the control system, and tune the controller on-line, if necessary.

rate components, as shown in Figure 3:

1. *Experimental Station: tanks, level sensors, level alarms, valves, and pumps*
2. *Process Station: hardware that carries out the control input-output and communicates between the Experimental Station and the Operator Station*
3. *Operator Station: PC-based system were Process Station information is monitored and modified*

The Process Station communicates with the Operator Station over a private TCP/IP network. The Freelance application package DigiTool was used to create a process database that is loaded onto the Process Station. The DigiVis application allows operator interaction with the Process Station and process database. Operator displays were created that allowed the students to operate the four-tank system (see Figure 4) as well as to track the trends of key operating variables (see Figure 5).

For the graduate control class, it is necessary to use more complex control algorithms than can be easily implemented using the Freelance packages. Matlab/Simulink can be used to calculate the control moves needed for the experimental system. A Dynamic Data Exchange (DDE) interface is used to link Matlab/Simulink with Freelance. The Simulink display (Figure 6) emulates a standard simulation flowsheet. By default, the Bailey DCS controls the process using manual or PID control. Once the student has "toggled" control (to Matlab from Bailey), however, the Simulink "simulation" drives the inputs to the Bailey system as the simulation proceeds. This creates a very flexible environment for implementing complex control algorithms on a moderately complex experimental system.

MATHEMATICAL DESCRIPTION OF THE PROCESS

Both a nonlinear model and a linearized model are given in Johansson and Nunes[3] for the four-tank system. The models used for this work include the disturbance effects of flows in or out of tanks 3 and 4. The nonlinear differential equations governing the heights in this four-tank system are given in Table 2, and the linearized version is seen in Table 3. The liquid levels in tanks one and two, h_1 and h_2, are considered measured variables. The speed of the pumps, v_1 and v_2, are considered as manipulated inputs. The pump speeds are manipulated as a percentage of the maximum pump speed. The disturbances d_1 and d_2 model the unmeasured disturbance effects of flows in or out of tanks three and four.

This model is a simple mass balance, assuming Bernoulli's law for flow out of the orifice. The gamma values, γ_i, correspond to the portion of the flow going into an upper tank from pump i. In Johansson and Nunes,[3] it is shown that inverse response in the modeled outputs will occur when

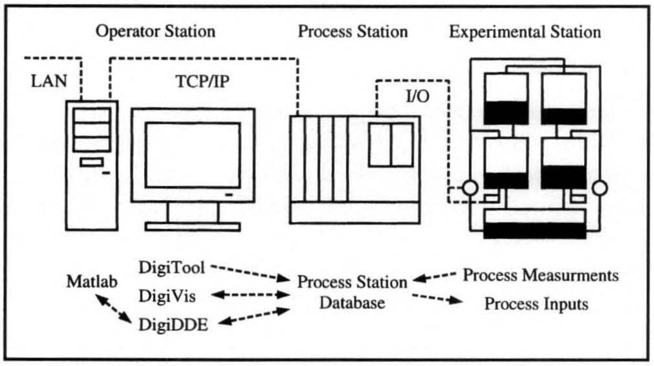

Figure 3. *Schematic of the control system.*

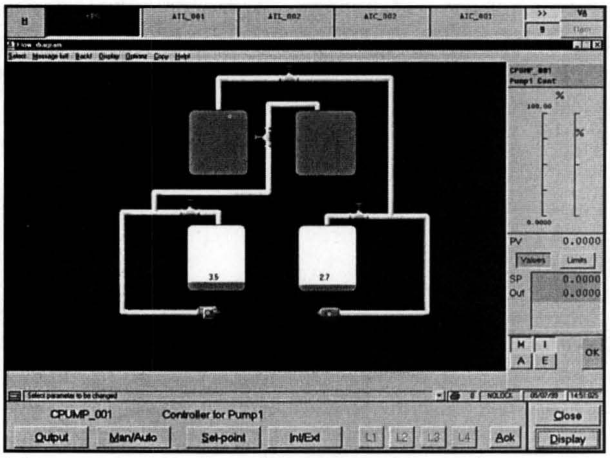

Figure 4. *Screenshot of Freelance four-tank schematic.*

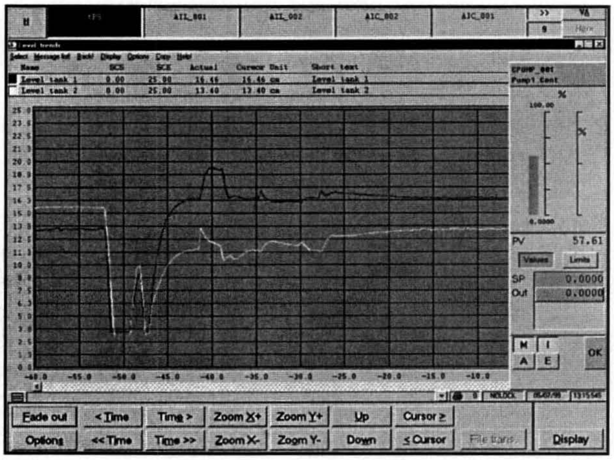

Figure 5. *Screenshot of Freelance tank-level trends.*

TABLE 2
Nonlinear Model Equations

$$\frac{dh_1}{dt} = -\frac{a_1}{A_1}\sqrt{2gh_1} + \frac{a_3}{A_1}\sqrt{2gh_3} + \frac{\gamma_1 k_1}{A_1} v_1$$

$$\frac{dh_2}{dt} = -\frac{a_2}{A_2}\sqrt{2gh_2} + \frac{a_4}{A_2}\sqrt{2gh_4} + \frac{\gamma_2 k_2}{A_2} v_2$$

$$\frac{dh_3}{dt} = -\frac{a_3}{A_3}\sqrt{2gh_3} + \frac{(1-\gamma_2)k_2}{A_3} v_2 - \frac{k_{d_1} d_1}{A_3}$$

$$\frac{dh_4}{dt} = -\frac{a_4}{A_4}\sqrt{2gh_4} + \frac{(1-\gamma_1)k_1}{A_4} v_1 - \frac{k_{d_2} d_2}{A_4}$$

TABLE 3
Linearized Model Equations

$$\frac{dx}{dt} = \begin{bmatrix} -\frac{1}{T_1} & 0 & 0 & 0 \\ 0 & -\frac{1}{T_2} & 0 & 0 \\ 0 & 0 & -\frac{1}{T_3} & 0 \\ 0 & 0 & 0 & -\frac{1}{T_4} \end{bmatrix} x + \begin{bmatrix} \frac{\gamma_1 k_1}{A_1} & 0 \\ 0 & \frac{\gamma_2 k_2}{A_2} \\ 0 & \frac{(1-\gamma_2)k_2}{A_3} \\ \frac{(1-\gamma_1)k_1}{A_4} & 0 \end{bmatrix} u + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -\frac{k_{d_1}}{A_3} & 0 \\ 0 & -\frac{k_{d_2}}{A_4} \end{bmatrix} d$$

$$T_i = \frac{A_i}{a_i}\sqrt{\frac{2h_i(0)}{g}}$$

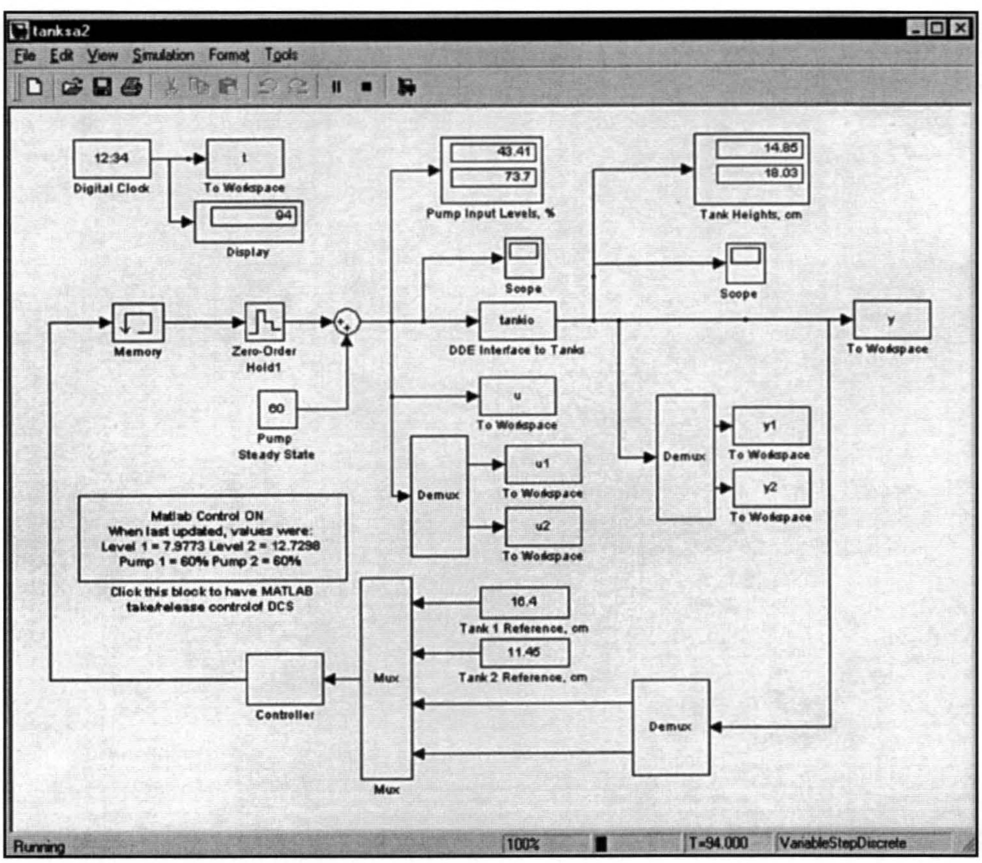

Figure 6. Screenshot of the Matlab interface.

$\gamma_1 + \gamma_2 < 1$. A modification introduced by the students in the class was the presence of a disturbance introduced by a submersible pump in the upper tanks. These disturbances' effects are modeled as a constant leak into or out of the upper tanks.

PROJECT SUMMARIES

To illustrate the use of the four-tank system in the graduate control course, the following projects are briefly described. It should be noted that each of the four elements (modeling, analysis, synthesis, and implementation) was performed by each student group. A more detailed theoretical treatment of the results can be found in Vadigepalli, *et al.*[4]

PROCESS IDENTIFICATION

Although the fundamental model described earlier is a reasonably accurate description of the system dynamics, many of the parameters are not available *a priori,* which required estimation of several model parameters. The tank areas A_i can be measured directly from the apparatus. Using tank drainage data, the cross-sectional outlet areas a_i can also be determined. The steady-state operating points of v_1 = 60% and v_2 = 60% were used for subsequent results. The system valves were set such that the operating point exhibits inverse response ($\gamma_1 + \gamma_2 < 1$). Time constants, T_i, for the linear system model were on the order of 40 seconds.

The students designed a suitable test input sequence to generate data for the estimation of the remaining parameters. In this case, they elected to identify the parameters of the original nonlinear model, requiring the solution of a nonlinear optimization problem. The problem was formulated to minimize the 2-norm of the difference between the nonlinear model and actual measurements, searching over four parameters. Using dynamic data from the experiments, the optimization routine found the optimal pump gains k_i and gamma values γ_i as depicted in Table 4. A similar routine was employed to model the characteristics of the disturbance introduced by the submersible pumps, k_{d_1} and k_{d_2}.

A critical step in any identification procedure is validation of the model against novel data. The students were successful in validating the model that resulted from the previous optimization problem. They were able to capture the known inverse response in the system, and they also were able to compare the nonlinear model response to a linear approximation, which was subsequently used for analysis.

TABLE 4
Model Parameters

a_1, a_2	2.3 cm^3	k_1	5.51 cm^3/s
a_3, a_4	2.3 cm^2	k_2	6.58 cm^3/s
A_1, A_2, A_3, A_4	730 cm^2	g	981 cm/s^2
$v_1(0)$	60%	γ_1	0.333
$v_2(0)$	60%	γ_2	0.307
T_1	53.8 sec	$h_1(0)$	14.1 cm
T_2	48.0 sec	$h_2(0)$	11.2 cm
T_3	38.5 sec	$h_3(0)$	7.2 cm
T_4	31.1 sec	$h_4(0)$	4.7 cm

ACCEPTABLE CONTROL ANALYSIS

As mentioned earlier, one of the key insights derived from this course is the limitation to achievable closed-loop performance due to intrinsic system properties. Once the students had obtained the physical models of the system, they computed a linearized approximation at a steady-state operating point and analyzed the controllability properties of the resulting linear system. The inputs and outputs of the system were appropriately scaled before the controllability analysis was carried out.

The first metric considered was the relative gain array (RGA) as a function of frequency. For the system configuration employed in this study, the students found that the diagonal RGA elements were very near to 1 at low frequency, suggesting an easily decoupled system. But as the frequency increased to the bandwidth region, the students discovered that the diagonal RGA values decreased significantly, indicating the importance of multivariable interactions in the bandwidth of interest. Such an insight is particularly valuable at the graduate control level to highlight the limited interpretation of the steady-state RGA value.

Additional insight is derived from an analysis of the singular values of the system. More specifically, their ratio (the condition number) gives an indication of the sensitivity of the plant to uncertainty. The condition number at low frequencies was small, between 1 and 3. But it decreases with frequency, implying that the plant is more sensitive to uncertainty at steady state than at higher frequencies. In addition, the low frequency minimum singular value is above 1. This means that adequate control action should be possible; the input moves will be able to move the outputs a sufficient amount to track setpoints. The minimum singular value of the plant is greater than 1 up to the frequency of ω=0.007 rad/sec. This indicates a potential constraint on the controller bandwidth because of high frequency input saturation.

Another quantity of interest in control systems in general, and the four-tank system in particular, is the location and direction of multivariable process zeros. For the operating conditions in this study, the multivariable zeros are found to be at -0.0791 and 0.0285 rad/sec. The input zero direction corresponding to the right-half-plane (RHP) zero is $[-0.715, 0.699]^T$, and the output direction is $[0.718, 0.696]^T$. From these directions, one can see that forcing one pump up while the other is forced down causes the system to display inverse response. The presence of the RHP-zero could also be seen in a plot of the RGA, in that the elements of the RGA change sign from frequency ω=0 to frequency $\omega = \infty$. The lesson that the students will take away from this analysis is that the RHP-zero also limits the controller bandwidth.

UNCERTAINTY CHARACTERIZATION

For completeness in the overall project description, the topic of uncertainty characterization is briefly mentioned. The technical details can be found in Vadigepalli, *et al.*[4] The emphasis was on bounding the uncertainty between the approximate linear model that was used for controller synthesis and the actual physical system with parametric uncertainty. A multiplicative input uncertainty structure was determined by the students to adequately represent the actual non-ideal behavior of the system. After subjecting the linear model to parametric variations (±10% in γ_i and k_i), approximate bounds were determined from the corresponding frequency plots of the multiplicative uncertainty. This uncertainty characterization is central to the robust controller design task that is described below.

ROBUST CONTROLLER DESIGN AND IMPLEMENTATION

The students employed robust control theory to initially design an H_∞ controller following the procedures detailed in Balas, *et al.*[5] Using a D-K iteration procedure, a robust 12th-order controller with a structured singular value, μ, less than 1 was obtained. The controller was implemented in the real system. As one might expect with a physical system, the simulations did not precisely match reality. The nonidealities of the pumps, level sensors, and head losses in the piping all contributed to these discrepancies. Other unmodeled phenomena witnessed by the students include the formation of vortices in the upper water tanks above the drainage holes and spontaneous triggering of the level alarms due to condensation. Despite the lack of perfect agreement between theory and practice, the students were able to generate controllers with robust performance guarantees.

Representative results demonstrating the disturbance rejection capability and setpoint tracking performance of one controller design are shown in Figures 7 and 8, respectively. This controller was designed for disturbance rejection, which results in excessive input moves for setpoint moves. A robustly performing setpoint tracking controller was also implemented. This design requires an additional setpoint filter in order to satisfy the constraints on the input moves.

The students clearly mastered a moderately complex control problem.

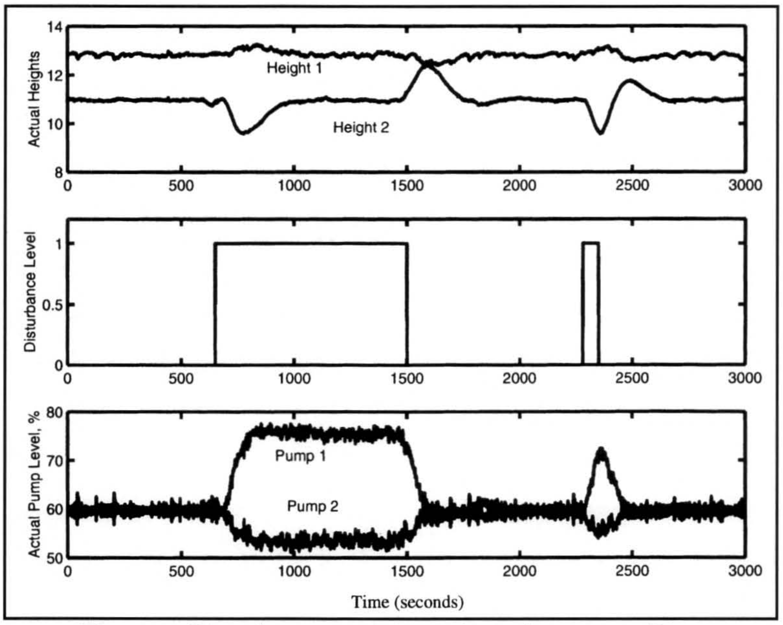

Figure 7. *Disturbance rejection using robust controller.*

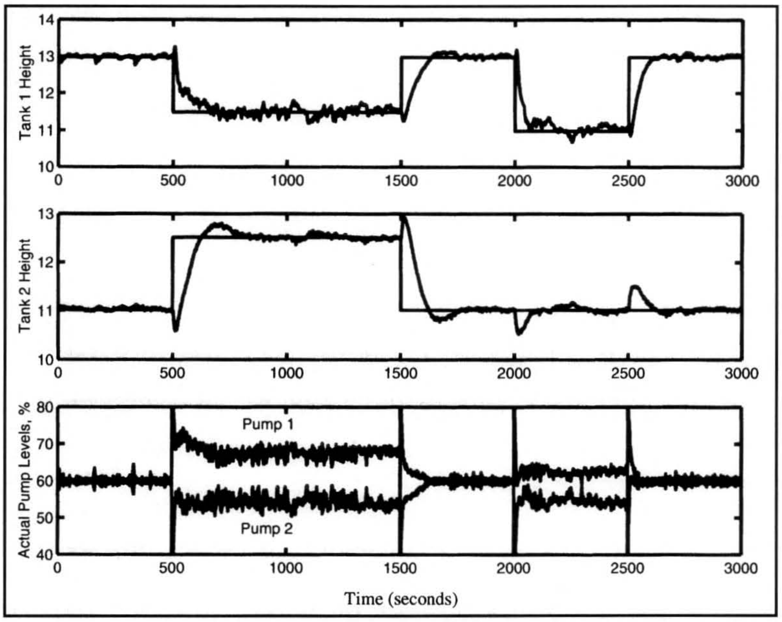

Figure 8. *Reference tracking using robust controller.*

SUMMARY

We have described the use of an elegant experiment for reinforcing the theoretical content of a typical graduate control course. Although the overall physics of the process are not very sophisticated, we have shown that the system exhibits rich behavior that can be used to exercise principles in modeling, analysis, and advanced control design.

The use of a PC-based DCS coupled with MATLAB/Simulink was particularly effective in the implementation of the laboratory control process. The PC-based system was more flexible than traditional DCS systems, and the DDE interface facilitated a range of complex control designs that are appropriate for the graduate level.

Our ongoing efforts with this experiment include the use of the four-tank system in a multidisciplinary control engineering laboratory. The course was first offered in the spring of 1999 as a senior-level elective and drew students from chemical, electrical, and mechanical engineering. We plan to report our experiences with this implementation in a future publication.

ACKNOWLEDGMENTS

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