A QUADRUPLE-TANK PROCESS CONTROL EXPERIMENT

EFFENDI RUSLI, SIONG ANG, RICHARD D. BRAATZ
University of Illinois at Urbana-Champaign • Urbana, IL 61801

While analytical calculations and process simulations[1,2] should be a key component in the education of a chemical engineer, students gain a deeper understanding of the nonidealities of industrial processes by carrying out experiments. Many industrial control problems are nonlinear and have multiple manipulated and controlled variables. It is common for models of industrial processes to have significant uncertainties, strong interactions, and/or non-minimum phase behavior (*i.e.,* right-half-plane transmission zeros). Chemical engineering students especially find the concept of right-half-plane transmission zeros to be more subtle than other concepts.

We designed a quadruple-tank process that was constructed to give undergraduate chemical engineers laboratory experience with key multivariable control concepts (see Fig. 1). By changing two flow ratios in the apparatus, a range of multivariable interactions can be investigated by using only the one experimental apparatus. Since the spring of 1999, this quadruple tank process has been used to teach students at the University of Illinois to

- *Understand control limitations due to interactions, model uncertainties, non-minimum phase behavior, and unpredictable time variations*
- *Design decentralized (often called "multiloop") controllers, and understand their limitations*
- *Implement decouplers to reduce the effect of interactions, and understand their limitations*
- *Implement a fully multivariable control system*
- *Select the best control structure, based on the characteristics of the multivariable process*

The quadruple-tank apparatus is a variation on an apparatus described in the literature[3] where we introduced a time-varying interaction between the tanks. This time-varying characteristic is caused by an irregularity in the fluid mechanics of splitting the stream into the upper and lower tanks, which results from the capillary effect of the tubing and dynamics of the multiphase flow of liquid and air in the tubing. The consequence of combining these factors is an enhanced sensitivity and stochasticity of the flow ratio to manipulated variable movements. The apparatus can exhibit a time-varying qualitative change in its dynamics, between conditions that are controllable to those that are uncontrollable. Although this uncontrollability issue has been reported as a major issue in large-scale industrial processes,[4] this appears to be the first educational laboratory experiment designed to clearly illustrate it and its effects on the control system.

The apparatus is small (1 ft x 1 ft x 6 in, not counting computer equipment) and is designed so the students, teaching assistants, and instructor can determine at a glance if the students are controlling the apparatus successfully. The small size enables experimental data to be collected rapidly and keeps the cost low. The apparatus is designed to be self-contained (that is, there are no requirements for continual access to water, steam, vacuum, or gas) and is environmentally friendly—the only chemical used is ordinary tap water, which is recycled during the experiments.

Past studies with 4-tank apparatuses implemented decentralized PI control,[3] multivariable H_∞ control,[3] multivariable internal model control,[5] and dynamic matrix control.[5]

Siong Ang *received his BS in chemical engineering from the University of Illinois under a Singapore Armed Forces Overseas Merit Scholarship and his MS from Stanford University. As part of his undergraduate thesis, he constructed quadruple-tank-process experiments and wrote the visual-programming control interface currently used in the undergraduate process control laboratory.*
Effendi Rusli *received his BS from the University of Wisconsin and his MS from the University of Illinois at Urbana-Champaign, both in chemical engineering. He is currently completing his PhD thesis on the analysis and control of systems described by multiscale simulation codes, with the main application being the electrodeposition of copper films and wires in microelectronic devices.*
Richard Braatz *received his BS from Oregon State University and his MS and PhD from the California Institute of Technology. After a postdoctoral year at DuPont, he joined the faculty at the University of Illinois, where he is a Professor and University Scholar. His main research interest is in multiscale systems theory and its application. He has published three books, one of which is a textbook on fault detection and diagnosis.*

The main educational focus of Ref. 3 was providing an apparatus with highly idealized and reproducible dynamics for use in illustrating multivariable interactions and multivariable transmission zeros. The main educational focus of Ref. 5 was to provide hands-on experience for students in implementing advanced control algorithms. In contrast, *our main educational focus is to aid students in understanding the advantages and disadvantages of the different control structures (e.g., decentralized, decoupling, multivariable) when applied to a multivariable process with interactions and dynamics ranging from highly ideal to highly nonideal.*

First, the construction of the apparatus will be described here in enough detail for duplication. Enough information will be provided for a technician or student to construct the control apparatus and for an instructor (who may not be an expert in control) to see how to use the experiment in the laboratory. This will be followed by motivation and background on the modeling and control for the apparatus. Some experimental results obtained by two students will also be presented to show how the apparatus illustrates some key control principles that are not addressed by past control experiments.

EXPERIMENTAL APPARATUS

A table of all equipment needed to construct the apparatus, including costs, can be obtained from the website at <http://brahms.scs.uiuc.edu>. Four cylindrical tanks are mounted vertically on an acrylic board and are arranged in a symmetric 2 x 2 fashion, as shown in Figure 1. A small hole is drilled at the bottom of each tank to channel the water from each to a differential pressure sensor via a 3/16-in tubing. MASTERFLEX tubings transport water between the tanks. Taking into account the maximum capacity of all four tanks (750 ml) and the dead volume inside the entire length of the tubings, a 1000-ml cylindrical beaker is enough to store and recycle water for the experiments. Two MASTERFLEX volumetric pumps are used. A 5-gallon tank immediately below the apparatus contains any spillage or splashing from overflow in any of the four tanks.

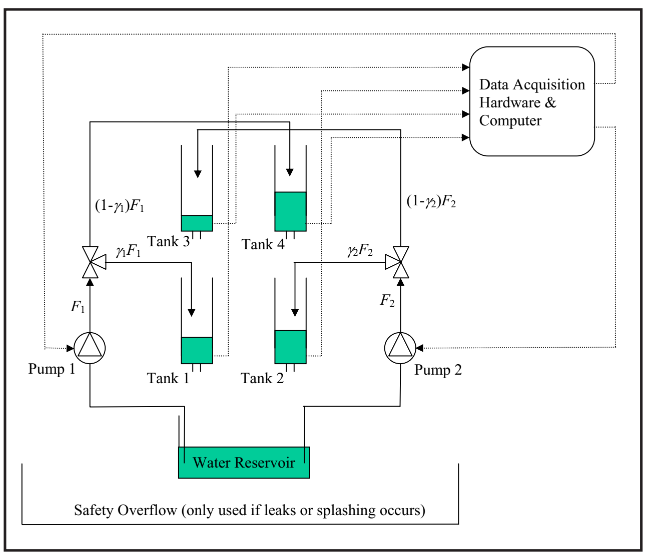

Figure 1. *Schematic of the quadruple-tank process apparatus. To simplify the figure, not shown are a tube between Tank 3 and Tank 1, a tube between Tank 4 and Tank 2, a tube from Tank 1 to the water reservoir, a tube between Tank 2 and the water reservoir, and a lid on the water reservoir. These tubes and lid are used to reduce evaporation.*

A Y-junction is used to divide the flow such that water is channeled to a bottom-level tank and the upper-level tank diagonal to it. This arrangement makes both levels in the bottom two tanks a function of both pump-flow rates. By adjusting the valve knob, the process can be operated so that one of the multivariable transition zeros is in the right-half plane, the left-half plane, or switches between the two planes in a stochastic time-varying manner.

The low cross-sectional area of the tanks makes level variations easy to see with the naked eye. Hence, students, teaching assistants, and instructors can assess the performance of the closed-loop system with a glance. The tank heights are small, so the closed-loop controllers that perform poorly lead to overflow in the tanks, which is an indication that the control system needs either better tuning or an alternative control structure, or the interactions need to be changed to make the process more controllable.

The visual programming control interface used in the laboratory[6] was modified for use with this apparatus. It enables students with a minimum background in computer programming to make changes in the control structures and is available for download at a web site.[7] Readers can find more details in the references.

MOTIVATION FOR THE APPARATUS

There are several advantages to including a quadruple-tank process experiment in an undergraduate chemical engineering laboratory. One is that the experiment can demonstrate a range of interactions from slight to very strong. The apparatus allows students to investigate the extent to which a decentralized controller is capable of controlling the process as the interactions increase. They can also implement partial or full decoupling as a first step to reduce process interactions. This enables students to obtain hands-on experience in how decoupling can improve the closed-loop performance in some situations (when there are some interactions, but not too strong), while having significant limitations when the interactions become sufficiently strong.[8]

The quadruple-tank dynamics have an adjustable multivariable transition zero, whose position can be in the left- or the right-half plane, depending on the ratio of flow rates between the tanks. This enables students to investigate performance limitations due to right-half-plane transmission zeros. For the particular quadruple-tank apparatus at the University of Illinois, under certain conditions the transmission zero can move between the left- and right-half planes, with varying levels of stochasticity depending on the operating condition. This leads to some interesting time-varying dynamics.

BACKGROUND

The experimental apparatus is used to teach important principles of process control while familiarizing chemical engineers with control structures used in industry. In the laboratory reports, students describe each learned control principle in words and illustrate the principle for the quadruple-tank process by first-principles modeling, applying control theory learned in lecture, and experimental verification. This draws a close connection between what the students learn in the lecture and what they practice in the laboratory.

The material balance equations using common assumptions and the transfer function matrix obtained by linearizing and taking deviation variables are given in Figure 2. The second-order transfer functions correspond to the contributions to the bottom two tanks by the upper two tanks. The linearized system G(s) in Figure 2 has two multivariable transmission zeros, which are determined by the zeros of its determinant

$$\det G(s) = \frac{c_1 c_2 \gamma_1 \gamma_2}{\prod_{i=1}^{4}(1+sT_i)}\left[(1+sT_3)(1+sT_4) - \frac{(1-\gamma_1)(1-\gamma_2)}{\gamma_1\gamma_2}\right] \tag{1}$$

It is important to determine the location of these zeros in the complex plane since right-half-plane zeros limit the closed-loop performance achievable by any control system.[8,9] For the sake of convenience, the parameter η is introduced as

$$\eta = \frac{(1-\gamma_1)(1-\gamma_2)}{\gamma_1\gamma_2} \tag{2}$$

where $\eta \in (0,\infty)$. Since the numerator of Eq. (1) is a quadratic, the zeros can be computed analytically

$$z_{1,2}(\eta) = \frac{-(T_3+T_4) \pm \sqrt{(T_3-T_4)^2 + 4T_3T_4\eta}}{2T_3T_4} \tag{3}$$

Given $T_3 > 0$ and $T_4 > 0$, the function in Eq. (3) is differentiable for $\eta \in (0,\infty)$.

$$z'_{1,2}(\eta) = \pm\frac{1}{\sqrt{(T_3-T_4)^2 + 4T_3T_4\eta}} \tag{4}$$

The derivatives exist for all conditions where $T_3 \neq T_4$. When $\eta = 0$, the zeros are $z_1 = -1/T_3$ and $z_2 = -1/T_4$. As η approaches ∞, it is straightforward to deduce from Eq. (3) that

$$z_1 \to \sqrt{\eta / T_3T_4} \quad \text{and} \quad z_2 \to -\sqrt{\eta / T_3T_4}$$

Because the derivative functions in Eq. (4) are monotonic, z_1 is strictly increasing and z_2 is strictly decreasing. This implies that the transmission zero z_1 will cross from the left-half plane to the right-half-plane with increasing η. The crossing occurs at $\eta = 1$. With a little algebra, these results can be written in terms of the flow ratios γ_1 and γ_2, as shown in Table 1.

The process is minimum phase when the total flow to the lower tanks is greater than the total flow to the upper tanks ($1 < \gamma_1 + \gamma_2 < 2$). The process is non-minimum phase (that is, has a multivariable transmission zero in the right-half plane) when the total flow to the lower tanks is smaller than the total flow to the upper tanks. For operating conditions where the total flow to the upper tanks is nearly the same as the total flow to the lower tanks, small variations in the flows due to irregular behavior in the tubing can cause the transmission zero to move between the two half planes in an irregular manner, in which case the process becomes uncontrollable.[9]

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

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

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

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

where

A_i	cross-section of Tank *i*
a_i	cross-section of the outlet hole
h_i	water level in Tank *i*
h_i^0	steady-state value for the water level in Tank i
γ_i	the fraction of water flowing to Tank *i* from Pump *i*
v_i	voltage applied to Pump *i*
$k_i v_i$	flow from Pump *i*
γ_i	fraction of flow going to Tank *i* from Pump *i*
g	acceleration due to gravity

$$G(s) = \begin{bmatrix} \dfrac{\gamma_1 c_1}{1+sT_1} & \dfrac{(1-\gamma_2)c_1}{(1+sT_3)(1+sT_1)} \\ \dfrac{(1-\gamma_1)c_2}{(1+sT_4)(1+sT_2)} & \dfrac{\gamma_2 c_2}{1+sT_2} \end{bmatrix}$$

where

$$T_i = \frac{A_i}{a_i}\sqrt{\frac{2h_i^0}{g}}, \qquad i = 1,\cdots,4.$$

$$c_1 = T_1 k_1 / A_1$$

$$c_2 = T_2 k_2 / A_2$$

Figure 2. *Physical models for quadruple-tank process.*[3]

TABLE 1

Location of Zeros on the Linearized System as a Function of the Flow Ratios γ_1 and γ_2

	z_1	z_2	
$1 < \gamma_1 + \gamma_2 \le 2$	negative	negative	minimum phase
$\gamma_1 + \gamma_2 = 1$	zero	negative	boundary
$0 \le \gamma_1 + \gamma_2 < 1$	positive	negative	nonminimum phase

More precisely, the steady-state determinant of the transfer function [G(0) in Figure 2] switches sign when $\gamma_1 + \gamma_2$ crosses 1, indicating that it is impossible to control the process with a linear time invariant feedback controller with integral action.[9] This is a generalization of the single-loop notion that the sign of the steady-state gain must be either consistently positive or consistently negative for the process to be controllable with a linear feedback controller with integral action.

Students have applied decentralized control, decoupling control, and fully multivariable control on the same apparatus. They compare different multivariable control structures and judge for themselves the most effective method to control the apparatus. It is important for the students to realize that the same structure can perform very differently and they will face a new set of limitations when conditions change. This is especially relevant to this particular apparatus in which under some conditions the process becomes uncontrollable during movement of the transmission zero across the imaginary axis within a single setpoint or disturbance response.

After investigating decentralized control, decoupling is implemented as the first step to deal with loop interactions. Students verify the improvement/deterioration in closed-loop

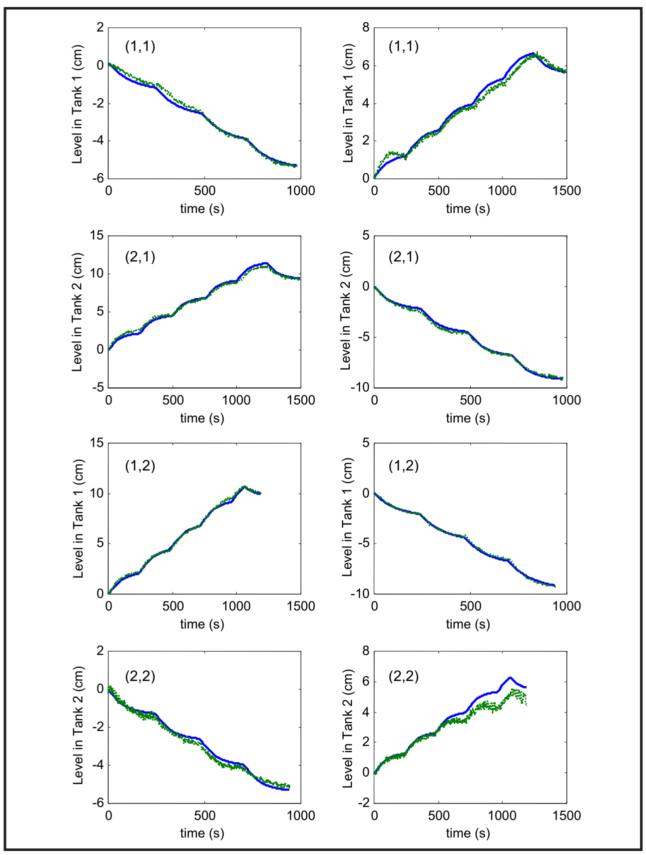

Figure 3. *Model predictions plotted with experimental data for the four elements of the transfer function matrix: data used to fit model (left), data used to verify model (right). The row and column numbers are reported in the upper-left-hand corner.*

performance caused by the implementation of decoupling. The details of the implementation vary depending on the type of decoupling (steady-state, dynamic, partial, full), but all of these are easy to implement using the control interface.[6] Students also investigate the effects of model uncertainties, which are especially important for this apparatus.

EXAMPLE IDENTIFICATION RESULTS

The identification experiment is an ascending series of steps followed by subsequent descending steps for identification, which is a better input for characterizing process nonlinearities. The use of ascending and descending step inputs has the educational benefit of permitting visual monitoring of the change in the dynamics with different level of operating regime and checking of the reproducibility of the process response.

To ease them into the process, students are prompted to first operate the apparatus so that most of the flow goes to the bottom two tanks. The first step is to determine the transfer function matrix for the experimental apparatus for comparison to the theoretical model. Various student teams have fit first-order-plus-time-delay, state space, and ARMAX models to experimental data. For brevity, only transfer functions determined using the program ms2th,[10] which is a MATLAB built-in identification subroutine, to compute the least-squares estimate of both discrete and continuous model parameters, are reported here for one operating condition:

$$y(s) = G(s)u(s) + H(s)e(s) \tag{5}$$

$$G(s) = \begin{bmatrix} \dfrac{11.89}{121.4s+1} & \dfrac{6.875}{(121.4s+1)(3.967s+1)} \\[2ex] \dfrac{6.738}{(84.73s+1)(3.109s+1)} & \dfrac{11.53}{84.73s+1} \end{bmatrix} \tag{6}$$

$$H(s) = \begin{bmatrix} 2.179\dfrac{2.074s+1}{121.4s+1} & 1.529\dfrac{(1.410s+1)(7.970s+1)}{(121.4s+1)(3.967s+1)} \\[2ex] 2.382\dfrac{8.75s^2+5.75s+1}{(3.109s+1)(84.73s+1)} & 1.652\dfrac{2.725s+1}{84.73s+1} \end{bmatrix} \tag{7}$$

where u(s) is the vector of voltage signals from the two pumps, y(s) is the vector of heights of Tanks 1 and 2, and H(s) has been normalized so that the noise signal e(s) is uncorrelated with unit variance. Comparing the theoretical transfer function model in Figure 2 with Eq. 7 gives the nominal estimates of the physical parameters

$$\gamma_1 = 0.63 \qquad \gamma_2 = 0.64 \qquad c_1 = 18.94 \qquad c_2 = 18.10$$

which would indicate that both transmission zeros are in the left-half plane (see Table 1). Figure 3 compares the predictions of the model (6) and experimental data. There is some variation in the gains, which agrees with an experimental observation that the flow ratios vary depending on the operating conditions and that the gains are a function of the flow ratios (see Figure 2). Using basic statistics,[11] the 95% confidence intervals for the flow ratios are $0.48 < \gamma_1 < 0.79$ and $0.49 < \gamma_2 < 0.80$, which suggest that the transmission zero may move into the right-half plane under some operating conditions. This has serious implications on feedback controller design, as seen below.

EXAMPLE MULTIVARIABLE CONTROL RESULTS

Full multivariable control such as model predictive control can be implemented that manipulates the signals to the pumps to control levels in the bottom two tanks.[5] While such multivariable controllers are being increasingly implemented in industry, other types of controllers have been applied in the chemical industries, such as

- ***Decentralized control****: a noninteracting controller with single-loop controllers designed for each tank. Control loop 1 manipulates the flow through Pump 1 (via a voltage signal) to control the height of Tank 1, while Control loop 2 manipulates the flow through Pump 2 to control the height of Tank 2.*
- ***Partial decoupling*** *followed by decentralized control.*
- ***Full decoupling*** *followed by decentralized control.*

Various students have implemented these control strategies on the quadruple-tank process apparatus during the past five years. Students implement up to three control strategies in a 7-week period, where the scheduled lab time is 3 hours per week and the lab report requirements include first-principles modeling, analysis, and comparison between theory and experiment.

The relative gain for the nominal plant (6) is 1.5, which indicates that Pump i should be paired to the level in Tank I (8). Decentralized Internal Model Control Proportional-Integral (ICM-PI) controllers are tuned to trade off robustness with performance[8,9,12] (see Table 2 and Figures 4 and 5 for two levels of tuning). Due to model uncertainties, the differences between model predictions and experiments are large when the IMC-PI controllers are tuning too aggressively.

Implementing a partial dynamic decoupler and multiplying by the transfer function matrix in Figure 2 gives

$$\tilde{G}(s)=\begin{bmatrix} \dfrac{\gamma_1 c_1}{1+sT_1} & 0 \\ \dfrac{(1-\gamma_1)c_2}{(1+sT_4)(1+sT_2)} & \dfrac{\gamma_2 c_2 \Theta}{(1+sT_2)(1+sT_3)(1+sT_4)} \end{bmatrix} \quad (8)$$

$$\Theta=(1+sT_3)(1+sT_4)-\frac{(1-\gamma_1)(1-\gamma_2)}{\gamma_1\gamma_2}$$

TABLE 2
Proportional Gains, K, and Integral Time Constants, τ_I for Decentralized Controllers with Aggressive and Sluggish Tuning

		K	τ_I
Aggressive	C_1	1	121.4
	C_2	1	84.73
Sluggish	C_1	0.378	121.4
	C_2	0.395	84.73

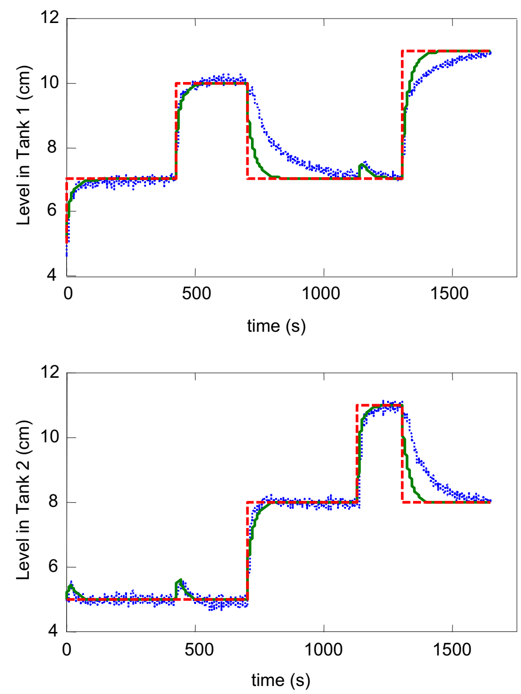

Figure 4. *Decentralized controller with aggressive tuning: setpoint (dashed line), experiment (dots), model prediction (solid line).*

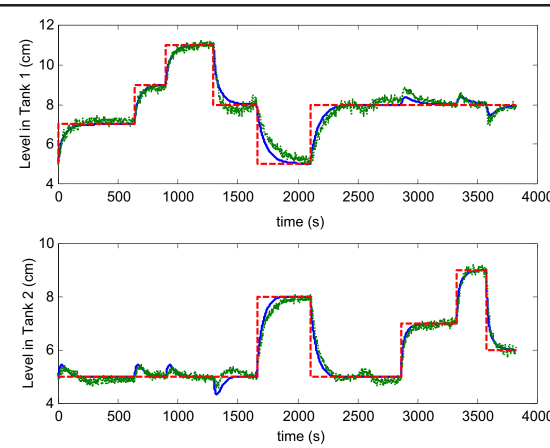

Figure 5. *Decentralized controller with sluggish tuning: setpoint (dashed line), experiment (dots), model prediction (solid line).*

TABLE 3
Proportional Gains, K, and Integral Time Constants, τ_I for Partially Decoupled Controllers with Aggressive and Sluggish Tuning

		K	τ_I
Aggressive	C_1	1	121.4
	C_2	1	84.73
Sluggish	C_1	0.3	121.4
	C_2	0.3	84.73

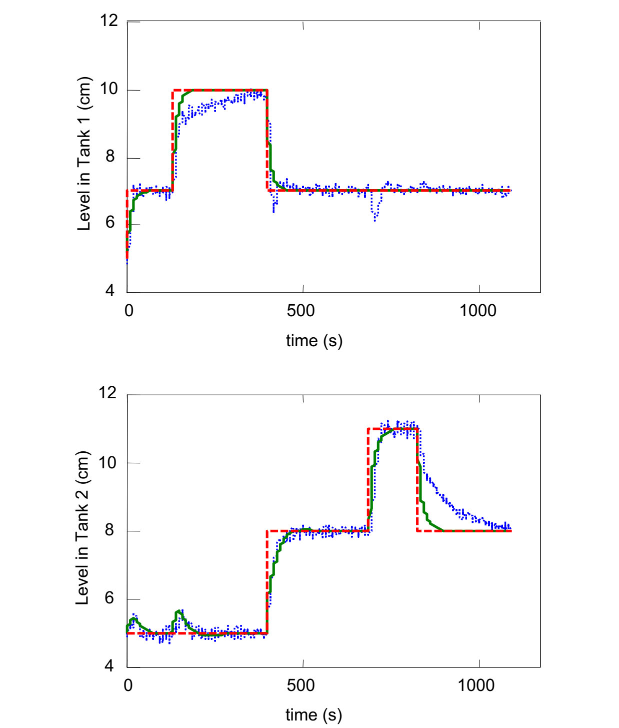

Figure 6. *Partial decoupling with aggressive tuning: setpoint (dashed line), experiment (dots), model prediction (solid line).*

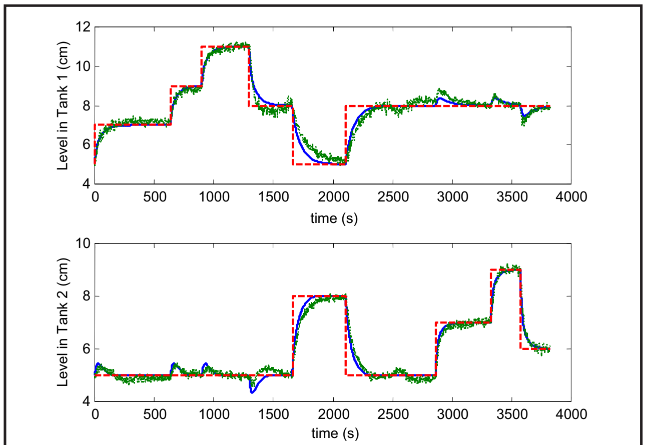

Figure 7. *Partial decoupling with sluggish tuning: setpoint (dashed line), experiment (dots), model prediction (solid line).*

The transmission zeros are values of s in which $\Theta = 0$ (see Eq. 5). Both transmission zeros appear in the second control loop. This results in a degradation of the closed-loop performance for the second control loop when one of these transmission zeros is in the right-half plane. Using model (6), the results of tuning IMC-PI controllers to trade off robustness with performance are shown in Table 3 and Figures 6 and 7. Both aggressive and sluggish tuning shows some interactions between the control loops, due to plant/model mismatch. The differences between the model predictions and experimental data are larger for the aggressive tuning.

While full dynamic decoupling is not common industrial practice, for educational purposes it is useful to compare full dynamic decoupling with partial dynamic decoupling to illustrate how full decoupling can lead to worse closed-loop performance than partial decoupling. Implementing a full dynamic decoupler and multiplying by the transfer function matrix in Figure 2 gives

$$\tilde{G}(s)=\begin{bmatrix} \dfrac{\gamma_1 c_1 \Theta}{(1+sT_1)(1+sT_3)(1+sT_4)} & 0 \\ 0 & \dfrac{\gamma_2 c_2 \Theta}{(1+sT_2)(1+sT_3)(1+sT_4)} \end{bmatrix} \quad (9)$$

The transmission zeros appear in both control loops. When one transmission zero is in the right-half plane, its effect on both loops implies that the closed-loop performance can be worse for full decoupling than for partial decoupling, since the right-half-plane transmission zero will affect both control loops. Using model (6), the model predictions and experimental data using the IMC-PI controllers in Table 3 are shown in Figures 8 and 9 (next page). The closed-loop responses with full decoupling are much worse than for the decentralized or partial decoupling controllers. In most cases when stepping up the setpoint, there appears to be inverse response exhibited in both control loops, suggesting that the closed-loop system is stable but a transmission zero has moved into the right-half plane. *That interpretation would be incorrect.* While it is correct that a transmission zero moves into the right-half plane when the setpoint is stepped up, the closed-loop system becomes *locally unstable* when this occurs. This is because the steady-state gains in (9) change sign, switching the controllers from negative to positive feedback. This is a common issue in large-scale industrial systems, which can be masked when physical constraints are present.[4,13-14]

To see the change in sign, consider the entry (2,2) in the transfer function matrices (8) and (9)

$$g_1(s)=\frac{\gamma_2 c_2 \Theta(s)}{(1+sT_2)(1+sT_3)(1+sT_4)} \quad (10)$$

Since $\gamma_2 c_2 > 0$, the sign of the steady-state gain of $g_1(s)$ is equal to the sign of $\Theta(0) = 1-(1-\gamma_1)(1-\gamma_2)/\gamma_1\gamma_2$, which changes sign when the process operating condition switches from minimum phase to non-minimum phase and vice versa (that is, when $\gamma_1 + \gamma_2$ crosses 1).

This local instability causes the initial decrease in tank levels. Decreasing the tank levels changes the relative magnitudes of the total flow rates between the top two tanks and the bottom two tanks, causing the right-half-plane transmission zero to move back into the left-half plane, the steady-state gain to change back to its original sign, and the closed-loop poles to move back into the left-half plane. The closed-loop system stabilizes, causing the tank levels to increase back towards the desired setpoints. This switch from closed-loop stability to instability and back to stability is why the initial decreases followed by increases in the tank levels are sharper than expected for a smooth system consisting of only low-order processes. There is no apparent "inverse response" in either control loops when stepping down the setpoint. While hysteresis is common in industrial process units such as valves, the case here is more interesting because it involves the movement of a transmission zero between the left- and right-half planes and a change in sign of the steady-state gains, resulting in very poor closed-loop performance obtained for a linear controller. (Although the essence of the argument is valid, for the student's sake this interpretation involves some simplification, since the real system is nonlinear.)

For this particular valve knob setting, the full decoupling controller induces this behavior more readily than the decentralized or partial decoupling controller. This illustrates the important point that when interactions are large enough, decoupling control can do more harm than good.[8,9] Full decoupling control has increased sensitivity to uncertainties in the transfer function model, which causes the ratios of the total flow rates in the bottom tanks and top tanks to vary more than for the other controllers. If the valve knob is shifted so that the transmission zero easily moves between the right- and left-half planes for the whole operating range (instead of only for some conditions, as in Figures 8 and 9), then good setpoint tracking is unobtainable by a linear controller, no matter how sophisticated.[9]

The second important point is that hysteresis effects are common in industrial control loops and should be considered when troubleshooting. The third point is that the cause of unexpected dynamic behavior in control loops is often more subtle than what is often first assumed. But such phenomena can be understood with some thinking and judicious application of undergraduate-level process control analysis tools. This understanding is needed to determine whether a particular control problem can be resolved by better controller tuning, a different control structure, by changing the process design, or by changing the operating conditions.

For the next experiment, the quadruple-tank process was made more interactive by using the Y-junctions to increase the proportion of flow to the top tanks. Closed-loop responses with decentralized control are shown in Figure 10. Due to the higher interactions, as well as some nonlinear effects, the closed-loop responses were highly oscillatory around the setpoints. The student was unable to obtain controller tuning parameters that would stabilize the closed-loop system when either steady-state or dynamic decoupling was used. The best closed-loop response obtained by dynamic decoupling is shown in Figure 11. The initial closed-loop performance was acceptable up to 200 s, but the level in Tank 2 deviated from

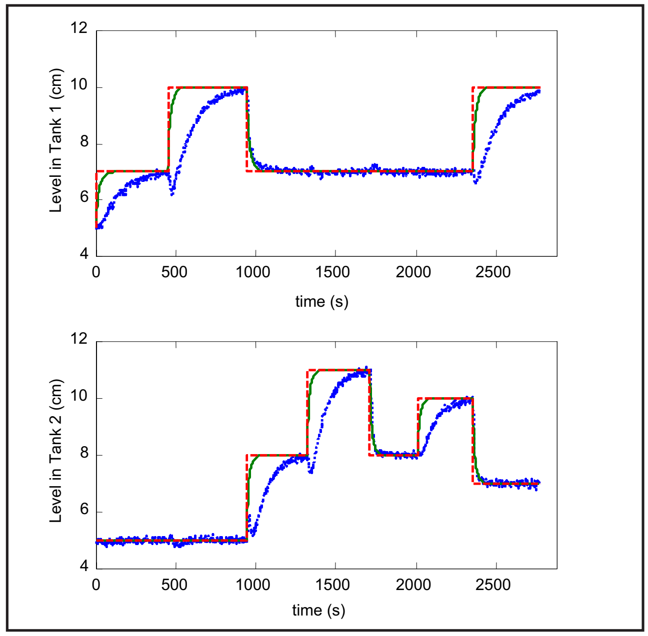

Figure 8. *Full decoupling with aggressive tuning: setpoint (dashed line), experiment (dots), model prediction (solid line).*

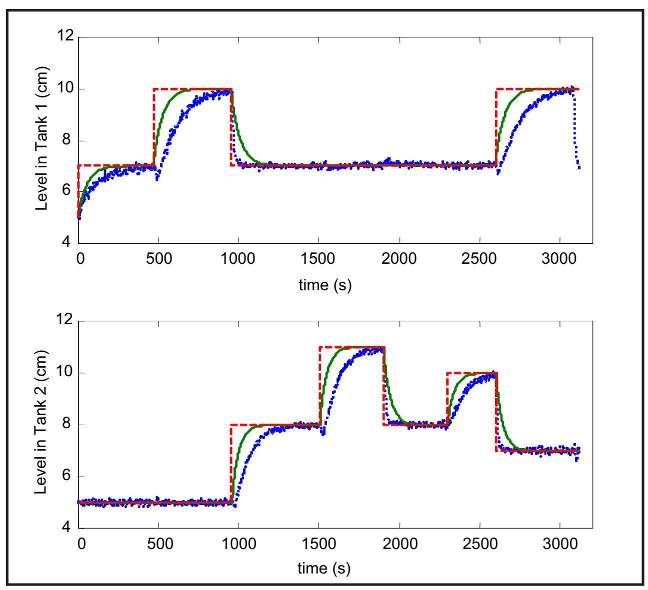

Figure 9. *Full decoupling with sluggish tuning: setpoint (dashed line), experiment (dots), model prediction (solid line).*

the setpoint for t > 400 s, indicating that the closed-loop system was not locally asymptotically stable. In addition, there was a consistent steady-state offset exhibited by the level in Tank 1. Again, this illustrates to students that a process that is designed poorly can be difficult or impossible to control.

Different student teams are given different valve settings in the Y-junctions, and students are encouraged to share their results with other teams. Students who consistently have >80% of the flow going to the bottom tanks observe that decoupling control can provide better closed-loop performance than multiloop control. Decoupling control performs worse than decentralized control when the interactions are increased. When the total flows to the top and bottom tanks are equal or nearly equal, no linear controller can provide acceptable closed-loop performance.

CONCLUSIONS

A 4-tank apparatus was introduced in which a multivariate transmission zero can cross the imaginary axis during a single closed-loop response, which is used to illustrate the effects of time-varying dynamics, changes in the sign of the steady-state gain, and hysteresis. Example student results illustrated how the apparatus is used to teach many important points that are ignored in most process control lectures and laboratories: 1) the effect of time-varying dynamics should be considered when designing control systems; 2) the sign of the steady-state gain should always be considered when designing control systems for multivariable processes; 3) the cause of unexpected dynamic behavior in control loops is often more subtle than what is first assumed; 4) under some conditions, full decoupling can lead to significantly worse performance than partial decoupling; 5) decoupling control can do more harm than good; 6) hysteresis effects should be considered when troubleshooting control problems. This level of understanding is needed for students to select the proper multivariable control structure and to determine whether a particular control problem can be addressed by better controller tuning, by a different control structure, by changing the process design, or by changing the operating conditions.

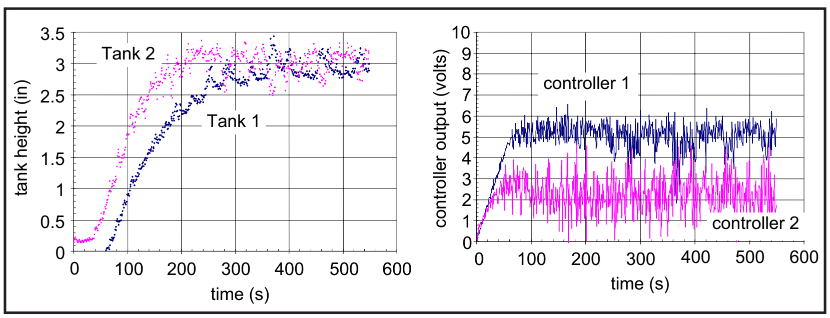

Figure 10. *Responses to decentralized control with setpoint heights of 3 inches in a strongly interacting system.*

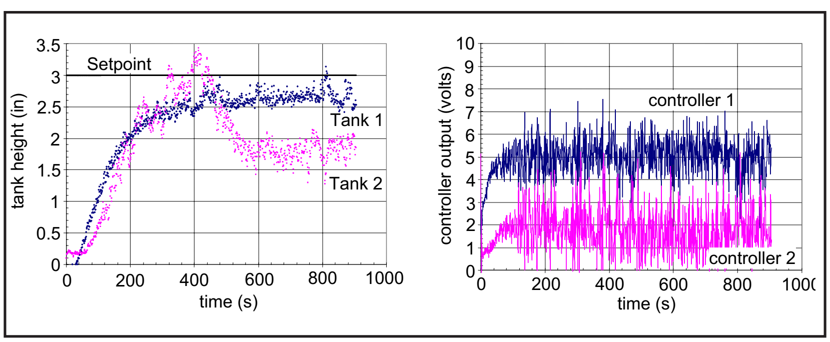

Figure 11. *Responses to dynamic decoupling control with setpoint heights of 3 inches in a strongly interacting system.*

Although not reported here, the apparatus has been used to implement partial and full steady-state decoupling, to compare with dynamic decoupling. Also, it would be educationally valuable to investigate the development of feedback linearizing controllers to enable a single controller to provide good performance for a wider range of operating conditions.[15]

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