A NONLINEAR, MULTI-INPUT, MULTI-OUTPUT
Process Control Laboratory Experiment

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The laboratory course in process control constitutes an important component of an undergraduate chemical engineer's education because it provides hands-on training in the application of process control to real processes. The laboratory course exposes the student to industrial process control hardware and the impact of measurement noise and unmeasured disturbances upon the control of real processes.

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In most university courses these laboratories are essentially linear single-input, single-output (SISO) unit operations. Until recently, the Department of Chemical and Petroleum Engineering at the University of Calgary was no exception. Yet such SISO control laboratories do not expose the student to the complexities of nonlinear or multi-input, multi-output (MIMO) processes.

A few laboratories in the literature[1-4] have attempted to address these shortcomings. Rivera at Arizona State University[1] describes a salt-mixing laboratory that examines the concentration dynamics at different tank levels using system identification techniques in a first process dynamics and control course. Fisher and Shah at the University of Alberta[2] describe a complex three-tank-level plus temperature arrangement that allows MIMO processes and process nonlinearity to be studied at the senior undergraduate or first-year-graduate course level. Braatz, *et al.,* at the University of Illinois[3, 4] describe a nonlinear but SISO pH neutralization process and a quadruple-tank apparatus that illustrates time-varying dynamics for a senior undergraduate process control course.

In this paper we describe a relatively simple salt-mixing laboratory in the undergraduate chemical engineering process control course at the University of Calgary that allows students to study both MIMO behavior and nonlinearity.

THE UNIVERSITY OF CALGARY'S PROCESS CONTROL COURSE

The University of Calgary requires process dynamics and control as part of the degree requirements for undergraduate students in chemical engineering, in a course that pioneered the hands-on, real-time (time domain) approach to teaching process dynamics and control.[5] Students in the class employ dynamic process simulation using a dynamic process simulator, such as HYSYS or Aspen Dynamics,[6] to model chemical process plants and their control systems. The students then create "disturbances" in the plant, which may involve changes in feed composition, flow, system temperatures, and/or pressures. The simulator demonstrates in real time what the effects of these "disturbances" would be on the plant operation, and it allows the student to evaluate the strengths and weaknesses of a given process control scheme.

The course is accompanied by a textbook written by the course instructors, *A Real-Time Approach to Process Control*.[7] The text has 10 chapters, each of which focuses on a given aspect of process dynamics and control, whether it be investigating the concepts of process gain, time constants, and deadtimes, studying control schemes for distillation columns, or examining plant-wide control. Associated with the chapters are eight workshops[8] that are to be completed by the student using a dynamic simulator. Each individual workshop explores the concepts explained in the associated chapter, allowing students to assign meaning to the words.

Due to the electronic nature of the workshops, hands-on, real-time experiments on laboratory unit operations equipment were considered a necessity to further reinforce the practical approach of the textbook. As a consequence, there is a compulsory laboratory component to the course.

LABORATORY OVERVIEW

The laboratory component of the process dynamics and control course includes two traditional experiments: (1) a three-tank cascade where simple process identification and level control are the objectives, and (2) a double-pipe heat exchanger with a variable deadtime leg which can be configured to investigate feedback, cascade, and feedforward control. While these experiments offer students the chance to experience the effects of process/measurement noise and unmeasured disturbances, the behavior of the experiments is essentially linear, and the control loop studied is SISO in structure.

SALT-MIXING LAB EXPERIMENT

The salt-mixing lab experiment that incorporates nonlinearity and MIMO behavior was designed in 2002 for immediate introduction into the curricula.

Figure 1 is a schematic of the laboratory process experiment. The following is a description of what occurs in the process:

> *A concentrated salt solution is mixed and stored in a large holding tank that was sized to give a five-hour or more run time. This solution is pumped into the conical mixing tank, passing through a magnetic flow meter and flow-control valve, which are used to regulate flow via a flow-control loop. Fresh water is supplied via building utilities; the water passes through a magnetic flow meter and control valve that are used in a flow-control loop to regulate the fresh-water flowrate. Upon entering the mixing tank the fresh- and saltwater streams are blended using a stirrer. The conical section of the mixing tank provides a strong process*

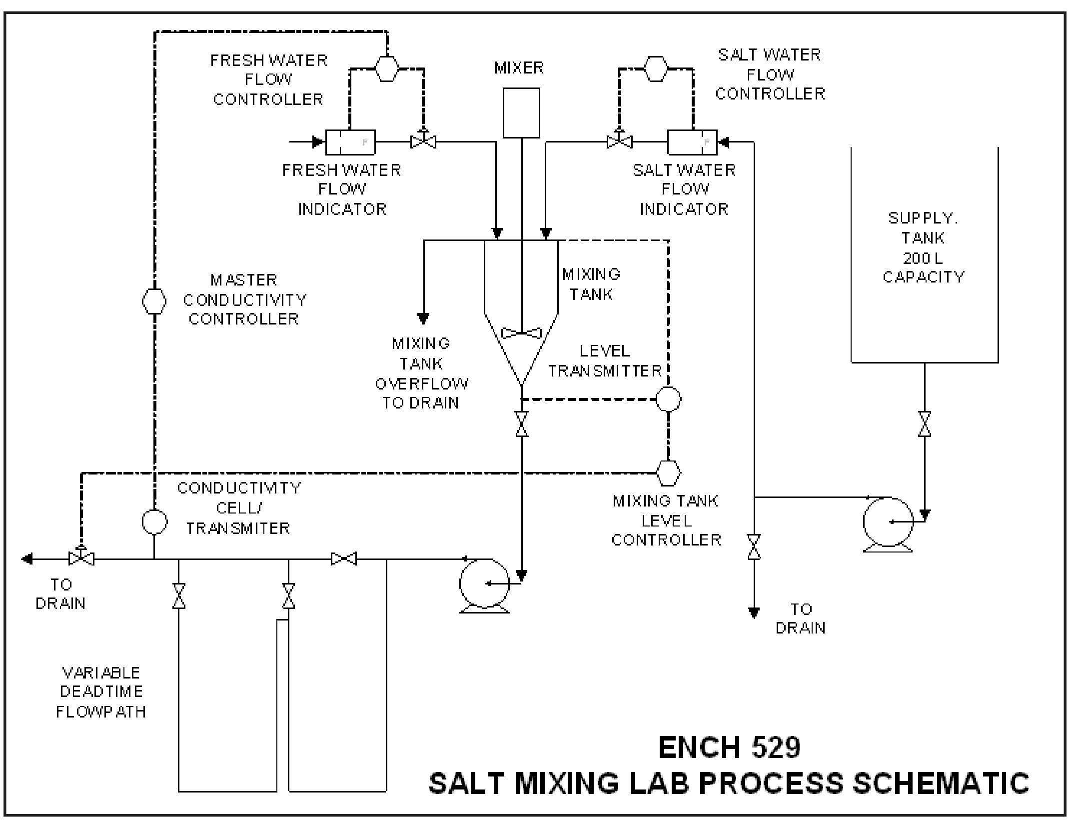

Figure 1. *A schematic of the Salt-Mixing Laboratory Process.*

nonlinearity. The level in the mixing tank is measured using a differential pressure cell. The blended solution enters a pump, is pressurized, and then moves to a pipe segment that allows for one of three flow paths of larger tube diameter to be selected. This setup allows one of three deadtimes to be examined. The stream will then pass through a conductivity cell/transmitter, which is used as the input to the master conductivity control loop. This loop's output is a cascaded setpoint to the slave fresh-water flow controller. Before going to drain, the stream passes through a control valve that is manipulated in order to regulate the level in the mixing tank. The flowrate, level, and conductivity inputs are all fed to the DCS system, as are the fresh-water, saltwater and level-control-valve-manipulated variables for this MIMO system. The input and manipulated variables are used within the DCS system with predefined function blocks to create the appropriate control loops.

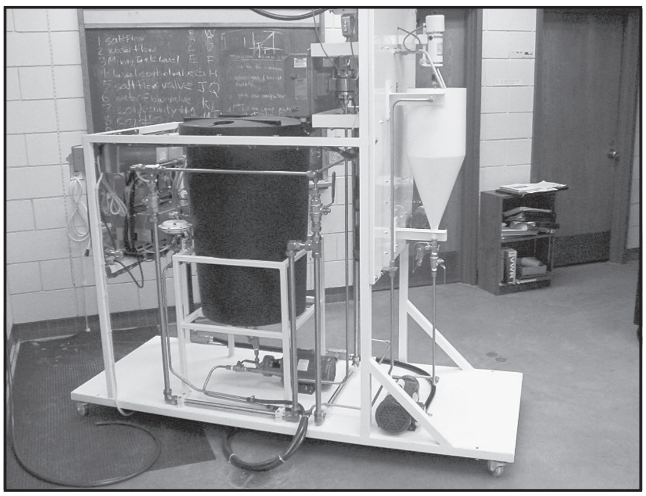

Figure 2. *A photograph of the Salt-Mixing Laboratory.*

Figure 2 shows the salt-mixing laboratory skid. The instrumentation, tank pumps, and additional parts were purchased from suppliers but the construction of the skid and commissioning of the equipment was completed in-house with the help of university support staff. This resulted in a compact unit that has capacity for expansion and is completely portable, allowing for more efficient use of laboratory space.

Figure 3 is a screen shot from the Emerson DeltaV distributed-control system (DCS) that is used for process data acquisition, monitoring, and control in the laboratory. The advantage of using a DCS is that they are common to modern industrial installations; as such, undergraduate engineering students should be taught what a DCS looks like as well as be provided with experience in controlling processes using such graphical interfaces.

Other laboratories in the literature[1, 9-11] have also realized this necessity and addressed it in different ways. Rivera, *et al.*,[1] also employed an industrial DCS (Honeywell, in that case), as did Skliar, *et al.*, at the University of Utah[9] in a graduate course also open to seniors (Opto 22, in the latter work). The approach of Bequette, *et al.*, at Rensselaer Polytechnic Institute[10] was perhaps the more typical use of Matlab/Simulink block diagrams as an interface to simulated experiments. Braatz, *et al.*,[11] employed the Hewlett Packard Visual Engineering Environment (HPVEE) to construct their student-operator interfaces to have a similar look and feel to an industrial DCS.

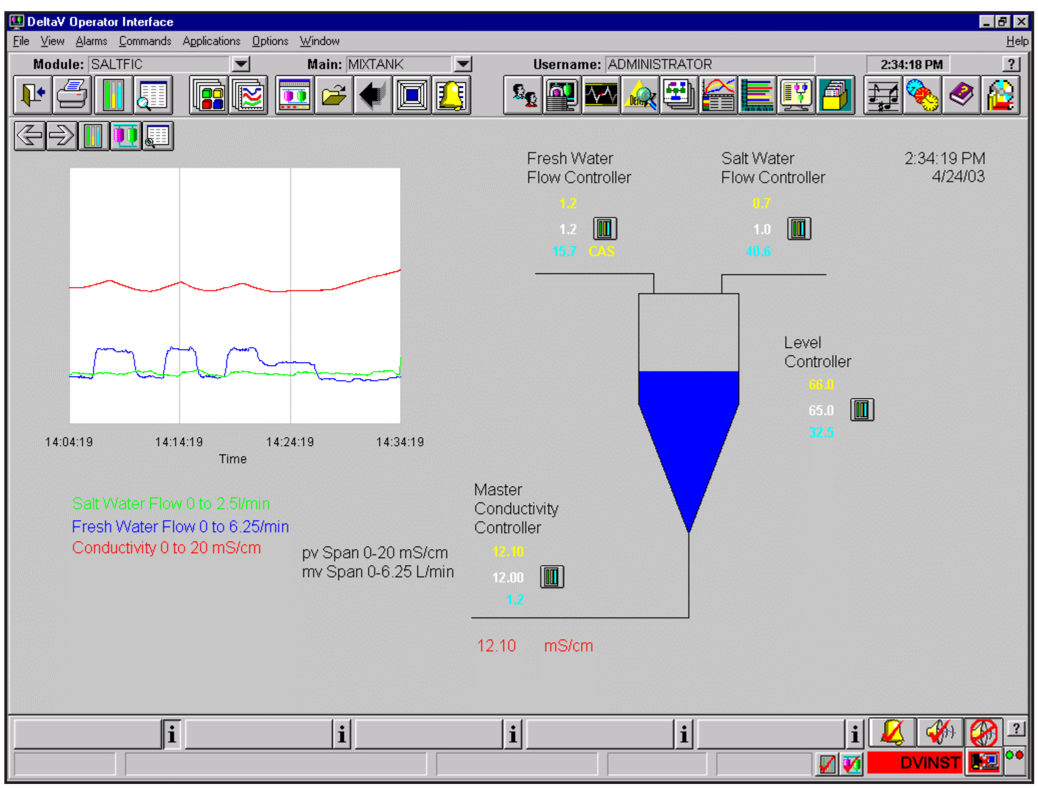

Figure 3. *A screen-shot from the DeltaV DCS.*

The overall mass and species balance equations that describe the dynamics of the system are included in Table 1, and the system nonlinearities are delineated and linearized in Table 2 so that the nonlinearities are clearer to non-control experts who have been assigned to teach process control. Figure 4 gives a time-domain plot from the DCS showing system response to saltwater flowrate changes from 0 to 0.5 then to 1.0 L/min (plus a few more). The effective tank-time constant varies with the flow.

TABLE 1
Overall Mass and Species Balance Equations

Overall Mass Balance Equation (Assuming constant density and isothermal)	$F_{\text{Fresh Water}} + F_{\text{Saltwater}} - F_{\text{Product}} = \frac{dV}{dt}$
Salt Species Balance Equation (Assuming constant density and isothermal)	$F_{\text{Saltwater}} . x - F_{\text{Product}} . y = \frac{d(Vy)}{dt}$

TABLE 2
System Nonlinearities

Nonlinearity	Nonlinear Characteristic	Linearized Characteristic
Volume change with level in the conical section	$V = \frac{1}{3}\tan^2\theta . h^3$	$V = \tan^2\theta . h_{op}^2 . h$
Product flowrate change with the level due to the valve	$F_{\text{product}} = K_v \sqrt{h}$	$F_{\text{product}} = \frac{K_v}{2\sqrt{h_{op}}} h$
Multiplicative nonlinearity between the volume and the salt concentration	$\frac{d(Vy)}{dt}$	$V\frac{dy}{dt} + y\frac{dV}{dt}$

LABORATORY TASKS

Myriad tasks can be done with the aforementioned apparatus. The purpose of this laboratory portion of the course is to allow students the opportunity to evaluate a variety of control schemes. To initiate this with the mixing-tank experiment, students set a tank level and then perform three step tests, where each step test is either an increase or a decrease from a nominal value. Tuning parameters (PI) are then calculated from the resulting process-reaction curves, using the students' choice of method (Cohen-Coon, Ziegler-Nichols, or IMC open-loop rules). The calculated tuning parameters are then compared with the tuning parameters obtained using the DeltaV automated tuning program (DeltaV tune), and both sets are tested by making setpoint changes or disturbances in the saltwater flowrate. The "best" set of tuning parameters is then chosen based on visual observations of the system response, including time to steady state, for each set of tuning parameters. With the best

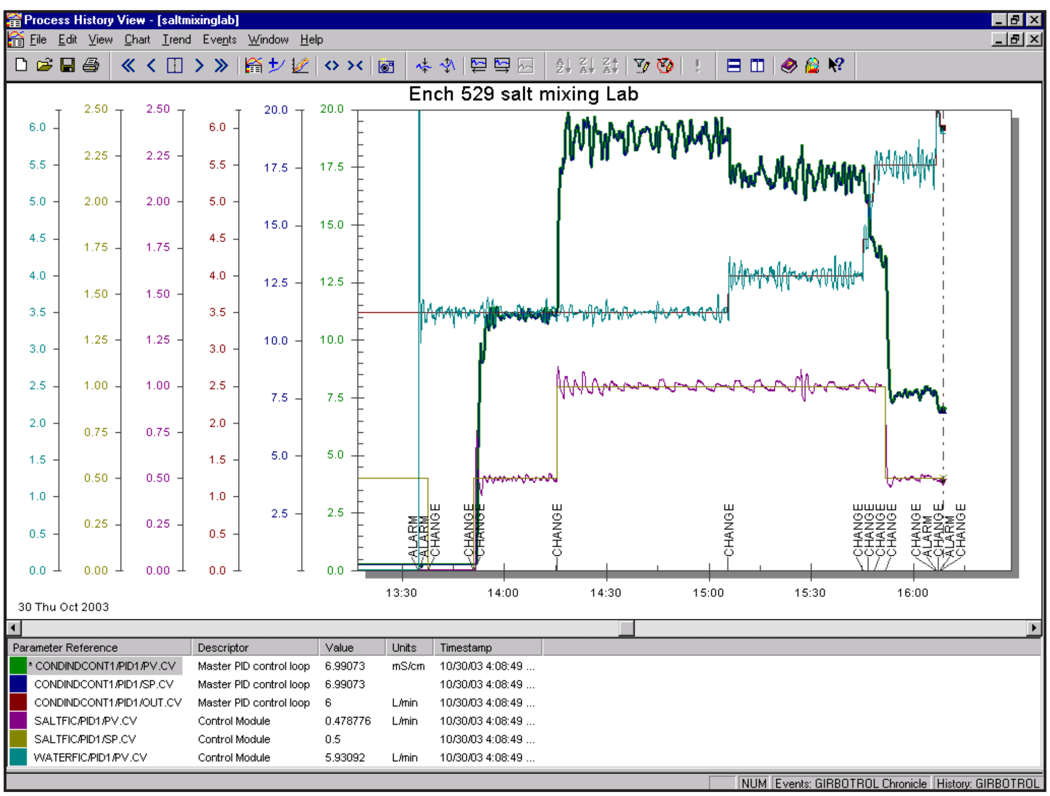

Figure 4. *A time-domain plot from the DCS demonstrating the system response to saltwater flowrate changes from 0 to 0.5 then to 1.0 L/min (plus a few more).*

tuning parameters entered into the system, the level in the mixing tank is then changed significantly, for example from 65% to 35%, which would mean moving from the cylindrical (linear) to the conical (nonlinear) section of the mixing tank or vice versa. Setpoint change(s) are then made in order to allow students to examine the process response.

The students are then asked to perform a full analysis of the process behavior in both open and closed loop, including comments on linearity, order of response, and possible better control strategies for the apparatus. As well, the students are given an additional open-ended problem: to calculate the amount of salt initially added to the storage tank. The information given to the students to complete these tasks includes printouts of process data (*e.g.*, flowrates, conductivity) and the initial height of water in the storage tank. Students are also able to measure the tank dimensions if they so desire.

The simulator demonstrates in real time what the effects of . . . "disturbances" would be on the plant operation, and it allows the student to evaluate the strengths and weaknesses of a given process control scheme.

EVALUATION

Along with an analysis of the process behavior, the students were asked to provide some general comments on the laboratory. Overall, the laboratory was found to provide good exposure to the latest process equipment, along with demonstrating different tuning methods (including those done using the built-in autotuner). Students were able to recognize the nonlinearity in the system and provide an explanation, as well as provide explanations for the changes in time constant and deadtime with different flowrates. System noise was well demonstrated in this laboratory and its effect on the graphical method for calculating tuning parameters was noted. As well, the effect of capacity was seen. Many students also attempted the open-ended problem—to calculate the initial mass of salt—and used a number of approaches in attempts to solve it. General student comments and laboratory reports indicated that students enjoyed working with the new laboratory experiment, and that it was helpful to see a real process that could provide them with a feel for what types of disturbances can be made in a plant. (Whereas, in the simulation workshops, unrealistic disturbances are quite possible and it is sometimes difficult to measure the actual time effect a disturbance would have.)

Because it was a real process, the students did find the experiment was a little long, as it usually ran slightly in excess of four hours (the time period scheduled for the experiment). A smaller process could be considered, but long time constants are a reality of industrial plants and this is an important fact for students to realize that is often somewhat overlooked in their process control education.

In general, it was felt that the laboratory was well received by students, and that it provided them with good exposure to state-of-the-art control hardware. The students were also exposed to instrumentation they had not seen before, such as magnetic flow meters and conductivity cells. The experiment also effectively displayed the difference between a simulation and a real process, in that it took up to 30 minutes to achieve steady state in closed loop, depending on the tuning parameters and the setpoint change made. Some ways in which this "down" time could be used more effectively include:

- *Quizzes*
- *Lab discussions*
- *Tutorial support*
- *Additional reading material*
- *Increased time to explain the apparatus*

These options could be used to keep the students focused on the experiment since it is felt that what was actually going on in the process was often overlooked due to other distractions during the time lags. Despite this, students did seem to take note of some pitfalls that can be encountered when tuning controllers, such as the errors associated with the graphical methods and the importance of proper input design.

The experiment also reaffirmed the value of a DCS in the teaching environment. Unit operations laboratories had previously had DCS systems integrated into them, but the DCS was not used in a control context and students did not need to make use of all of the data-collection and handling capabilities of the system. This experiment also showed a practical application of cascade control as the fresh-water supply pressure was not regulated—therefore changes in the water system would propagate through the system but would be quickly compensated for by the slave fresh-water flow-control loop that is manipulated by the master-conductivity control loop.

It was felt that the bonus question worked well and that it should be made mandatory for future labs. It was also convenient for the teaching assistants that the lab could be run differently for each group by simply changing the initial salt concentration or flowrates. As well, this changeability provided the teaching assistants with an opportunity to learn more about process control.

Overall, it was thought the lab performed very well and showed much promise as well as many other areas of potential use. For instance, it would be useful in a more advanced process control course where it could be used to demonstrate system identification and model predictive control in a practical setting.

CONCLUSIONS

The introduction of this new lab was successful from the students' point of view. They enjoyed working with the latest process control instrumentation. They also gained a new appreciation of the problems associated with real plants, in the form of noise and unexpected disturbances. The comparison of conventional open-loop tuning methods and an automated tuning package was appreciated, as was the chance to show their creativity in the solution of the open-ended bonus question.

From the instructors' point of view, the laboratory was considered successful. The only real concerns with the lab were based on the length of time it took to complete. This will be addressed in coming years with the introduction of quizzes and discussion while waiting for the process to reach steady state. Despite these concerns the lab provided an effective demonstration of a nonlinear and MIMO system. Most importantly, it was felt the students were better able to understand process behavior by being able to see many of the classroom concepts on an actual process. The department also gained a valuable tool for additional process control courses due to this lab's ability to have the control configuration changed, the ease in which it can be upgraded or modified, and its extensive data-collection and data-handling capabilities.

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NOMENCLATURE

- F volumetric flowrate [m^3/min]
- h level [m]
- h_{op} level at the operating point [m]
- K_v valve coefficient [$m^3/min.m^{1/2}$]
- θ slope of conical section [radians]
- t time [min]
- V fluid volume [m^3]
- x Inlet salt concentration [kg/m^3]
- y Outlet salt concentration [kg/m^3]

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