# EXPERIMENTAL PROJECTS FOR THE PROCESS CONTROL LABORATORY

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Digital control has been used in the Department of Chemical Engineering at the University of Illinois more than twenty-five years, but the process control laboratory underwent a major renovation and expansion from 1994-2000, in which the total number of control apparatuses was increased from a dozen to twenty-six (some of the apparatuses are duplicates). The cost for lab renovation was approximately $100,000, and the lab is maintained by a teaching assistant working fewer than ten hours per week. This expansion enabled all University of Illinois seniors (approximately 80 students/4 lab sections) to take the process control course in one semester, working in groups of two students during lab. Also, a modern control interface was designed and implemented in HP-VEE, which is a modern visual programming environment for instrument control.[1] The twenty-six control apparatuses include

1. *Temperature control in an air bath*
2. *Water-flow control under oscillatory load disturbances*
3. *Single-tank pH control*
4. *Interacting water-tank level control*
5. *Temperature control with variable-measurement time delay*
6. *Integrating tank-level control*
7. *Cascade control of temperature in a water tank*
8. *Dye-concentration control with load disturbances*
9. *Four-tank water-level control*
10. *Temperature and level control in a water tank*
11. *Multitank pH control*

The experiments were designed based on three underlying principles. First, the experiments should emulate real industrial processes and the control problems associated with those processes. Second, collectively the apparatuses should teach students a wide variety of techniques for addressing chemical process control problems. Third, the students should communicate with the apparatuses via a modern control interface.[1] Following these principles ensures that the students receive the appropriate training to productively solve control problems they may encounter in the industry.

The last three control apparatuses are the most sophisticated. Control apparatus #9 is similar to an apparatus in Professor Frank Doyle's control lab at the University of Delaware[2] and in a control lab at the Lund Institute of Technology.[3] The apparatus is used to teach multiloop and decoupling control and to illustrate how the controller design becomes more difficult as the interactions increase. Control apparatus #10 uses two oversized valves as the final actuation devices and temperature, water level, and two flow rates as the measured variables. This two-input four-output process is controlled using multivariable cascade control. Control apparatus #11, the multitank pH control apparatus, is a novel lab apparatus that exhibits significant nonlinearity.[4] In addition to a multiloop control strategy, students can also apply feedforward-feedback control loops and observe the dependence of their performance on the accuracy of disturbance models.

## SOFTWARE AND HARDWARE IN THE PROCESS CONTROL LABORATORY

A laboratory course in process control constitutes an important component of a chemical engineer's education.[5,6] It should provide hands-on training in the application of control to real processes. The design of the process control laboratory is instrumental to the quality of a chemical engineering education.

Figure 1 shows the flow of information between the computer hardware and the physical apparatus. Each computer is connected to a wet-lab experiment and an air-bath experi-

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ment. Modern industrial process installations have graphic operator interfaces for communication between the process control engineer and the industrial process. Undergraduate engineers should be exposed to such a graphic user interface and be provided with experience in controlling real processes using such interfaces.[5,6] The interfaces are designed to have the professional look and feel of real industrial operator interfaces, exposing students to a realistic control environment.

The Hewlett Packard Visual Engineering Environment (HP-VEE) is a visual programming language designed for instrumental control.[7] This software uses boxes to represent processes and controllers, and lines to represent information flows. The software has advantages over traditional programming languages. The visual interface of HP-VEE allows novice users to quickly master its programming language and therefore encourages more active student participation. Getting the program to work in a certain manner merely requires changing line connections between boxes or modifying control structures. Every change is a few mouse clicks away. The program is also equipped with debugging capabilities with direct reference to the error source, thus reducing time spent for debugging. More advanced algorithms such as model predictive control[8] can be implemented by linking to compiled programs written in popular languages such as Fortran or Visual Basic. For identification, the data are imported to Excel, and the parameters are fit using a variety of fitting routines. To assist the students in programming, an HP-VEE program is stored in the server for reference. The latest version of HP-VEE is called Agilent VEE.

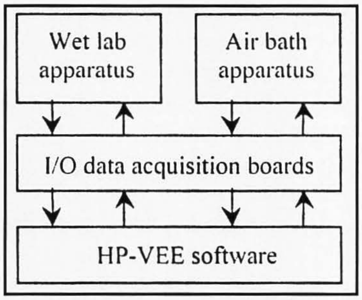

***Figure 1.** Computer hardware/ software architecture.*

## DESCRIPTION OF THE UNDERGRADUATE PROCESS CONTROL COURSE

The control class covers a broad range of control topics relevant in industrial problems encountered today. The syllabus includes first-principles modeling, process identification, and both single-loop and multivariable control systems. Students are exposed to a wide variety of real-life control restrictions such as time delays, non-minimum phase zeros, model uncertainties, unmeasured disturbances, measurement noise, and ill-conditioning.

Students have three hours of lectures and three hours of laboratory per week. The students spend about four hours per week outside of class to study for this course. The allocated lab time is sufficient for students to complete the lab. Students apply techniques in the laboratory shortly after they are covered in a lecture. Table 1 shows how the lecture topics are coordinated with lab experiments. The first series of laboratory sessions are devoted to an air-bath experiment from which students gain familiarity with the HP-VEE software, first-principles modeling, parameter estimation, filtering, on-off control, and single-loop PID control. This training prepares them for the second series of laboratory sessions, which are more open-ended and demanding. The students are split into several teams, with one wet-lab project assigned to each team. During the first three weeks of these experiments, the students write a visual program in HP-VEE to control the wet-lab experiment and carry out open-loop identification experiments. In

**TABLE 1**
**Course Schedule**

| Week | Lecture | Lab |
|---|---|---|
| 1 | Introductory concepts | |
| 2 | Review: mathematical modeling & Laplace transform | Introduction to control lab<br>Review of lab equipment |
| 3 | Building transfer function models<br>Dynamics of simple processes | On/off control of air bath |
| 4 | Higher-order dynamic behavior<br>Stability | Response of a shielded thermocouple |
| 5 | Nonlinear systems, linearization<br>Parameter estimation | Response of a shielded thermocouple |
| 6 | Feedback control, introduction to PID | PID air bath temperature control |
| 7 | Closed-loop time response and stability | PID air bath temperature control |
| 8 | Direct synthesis<br>Introduction to frequency domain | PID air bath temperature control |
| 9 | Frequency domain identification and analysis | Group project: open-loop identification |
| 10 | Cascade control<br>Feedforward/ratio control | Group project: open-loop identification |
| 11 | Review | Group project: open-loop identification |
| 12 | Introduction to MIMO systems<br>Interaction Analysis | Group project: model, design, and implement controllers |
| 13 | Design of decouplers<br>Model predictive control | Group project: model, design, and implement controllers |
| 14 | On-line optimization<br>Statistical process control | Group project: model, design, and implement controllers |
| 15 | Case study: distillation columns, packed-bed reactors | |

the remaining weeks the students construct process models, design controllers, implement the controllers on the laboratory apparatus, analyze the results, and write lab reports. The analysis is required to include a comparison between theoretical predictions and laboratory results with a discussion of potential causes for disagreement. The suggested work schedule is shown in Table 2.

## LABORATORY PROJECTS

To achieve a flavor for the experiments, the air-bath and some individual wet-lab experiments are described below. Table 3 provides a summary of the inputs and outputs of the data acquisition boards to the experimental projects.

### *Temperature Control in an Air Bath*

This apparatus dominates the laboratory curriculum as it is studied by all students during the first seven weeks of class. An air bath measures 12 in by 10 in and is available at all computer terminals. Its temperature is measured by a thermocouple, and its measurement is sent to the computer running the HP-VEE program. A fan keeps the air well-mixed. The manipulated variable in the process is the voltage sent to a blackened light bulb (see Ref. 1 for apparatus schematic). This air-bath experiment serves partly to familiarize students with the HP-VEE software as students will be expected to develop a control algorithm for their assigned wet-lab experiments. The students are asked to model the air bath and develop simplified models.

Step changes are performed to derive the process parameters used for controller tuning. The students apply first-or-

**TABLE 2**
**Proposed Schedule for Wet-Lab Experiments**

| | |
|---|---|
| Week 1 | • Familiarize with the equipment for the wet-lab experiment.<br>• Construct a block diagram showing all equipment.<br>• Derive transfer function models for all the blocks and clearly identify which model parameters can be looked up or directly measured and which must be determined from process reaction curves.<br>• Propose a control strategy that will satisfy the given control objectives and further familiarize yourself with the software. |
| Weeks 2/3 | • Make changes in the visual program to record all measurements, send all manipulated variable moves computed by the controller to the laboratory apparatus, save all variables of interest to the data file, plot all variables in the correct units.<br>• Implement open-loop step responses. |
| Week 4 | • Construct models from process response curve experiments. |
| Week 5 | • Implement control algorithms and collect closed-loop response data. |
| Week 6 | • Analyze data and compare theory with both open-loop and closed-loop experiments.<br>• Write lab report. |

**TABLE 3**
**Summary of Information of Experimental Projects**

| # | Qty | Experiment | Algorithm | Inputs (I/P) of Acquisition Board | Outputs (O/P) of acquisition board |
|---|---|---|---|---|---|
| 1 | 13 | Air bath | SISO | I/P 00-Bath temperature (°C) | O/P 00-Bulb voltage (V) |
| 2 | 1 | Oscillatory load | SISO | I/P 00-Flow rate (V) | O/P 00-Valve voltage (V) |
| 3 | 1 | Single-tank pH | SISO | I/P 00-pH level (no units) | O/P 00-Base pump voltage (V) |
| 4 | 1 | Liquid level | Single cascade/MIMO cascade | I/P 00-Flow rate to upper tank (V)<br>I/P 01-Upper tank height (inch)<br>I/P 02-Flow rate to lower tank (V)<br>I/P 03-Lower tank height (inch) | O/P 01-Valve voltage (V) |
| 5 | 3 | Temperature time delay | SISO | I/P 00 thru 03-Temperature (°C) | O/P 00-Pump voltage (V) |
| 6 | 1 | Integrating tank | SISO with P controller | I/P 00-Tank height (inch) | O/P 00-Pump voltage (V) |
| 7 | 1 | Temperature cascade | Single cascade | I/P 00-Tank temperature (°C)<br>I/P 01-Flow rate of hot water (V) | O/P 01-Valve voltage (V) |
| 8 | 1 | Dye concentration | SISO | I/P 00-Absorbance (no units) | O/P 00-Pump voltage (V) |
| 9 | 1 | Liquid level & temperature | MIMO cascade/Multiloop | I/P 00-Tank temperature (°C)<br>I/P 01-Flow rate of hot water (V)<br>I/P 02-Tank height (inch)<br>I/P 03-Flow rate of cold water (V) | O/P 00-Cold water valve (V)<br>O/P 01-Hot water valve (V) |
| 10 | 2 | 4-tank | 2x2 MIMO/Multiloop/Decouplers | I/P 00-Tank 1 height (inch)<br>I/P 01-Tank 2 height (inch)<br>I/P 02-Tank 3 height (inch)<br>I/P 03-Tank 4 height (inch) | O/P 00-Pump 1 voltage (V)<br>O/P 01-Pump 2 voltage (V) |
| 11 | 1 | Multi-pH | 3x3 MIMO/Multiloop/Feedforward | I/P 00-pH of Tank 1 (pH units)<br>I/P 01-pH of Tank 2 (pH units)<br>I/P 02-pH of Tank 3 (pH units)<br>I/P 03-pH of Tank 3 (pH units) | O/P 00-Base pump 1 voltage (V)<br>O/P 01-Base pump 2 voltage (V)<br>O/P 02-Base pump 3 voltage (V)<br>O/P 03-Acid pump voltage (V) |

der and second-order filtering to the data with a variety of filter time constants, to reduce the effect of measurement noise on their estimates. Students then apply a variety of tuning rules (e.g., Cohen Coon, direct synthesis, internal model control[8, 10, 11, 12]) to design PID controllers and compare the closed-loop performance obtained with each tuning rule. The students also apply an on/off control, where the bulb either switches completely off or on based on the sign of the offset. Students are asked to compare the performances of both types of control. The air-bath apparatus is the simplest and least expensive of all the apparatuses in the lab. We recommend that instructors interested in building a similar lab start with the air-bath apparatus.

❑ ***Water-Flow Control under Oscillatory Load Disturbances*** The objective is to control the flow rate downstream of a valve while the pressure downstream of the valve is continuously varying. The downstream pressure oscillates by varying the liquid level in a tank downstream from the valve using a float system, which is separate from the computer. The flow rate downstream from the valve is measured as a pressure difference across an orifice. A transducer measures this pressure difference as a voltage, which is sent to the data-acquisitions board in the computer (Figure 2).

Students construct process-reaction curves with respect to valve voltage. When analyzing these curves, the oscillations are significant. By first subtracting the oscillatory disturbance, a process gain, time constant, and time delay can be determined. Several PI and PID tunings are used for varying magnitudes of the oscillation. A goal of this experiment is to obtain some understanding of the effect of disturbances on the measured variable and that modeling the disturbances can result in improved input-output models and improved closed-loop performance.

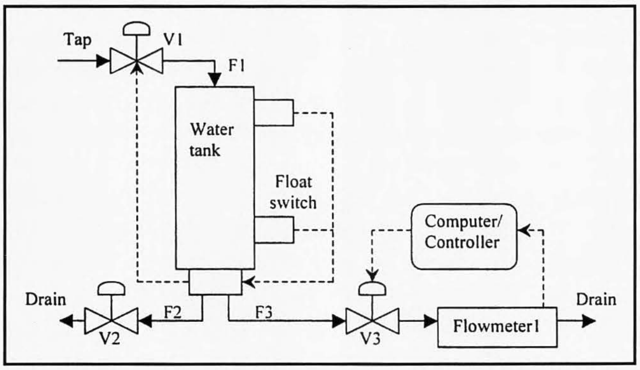

***Figure 2.*** *Water-level control under oscillatory load disturbances.*

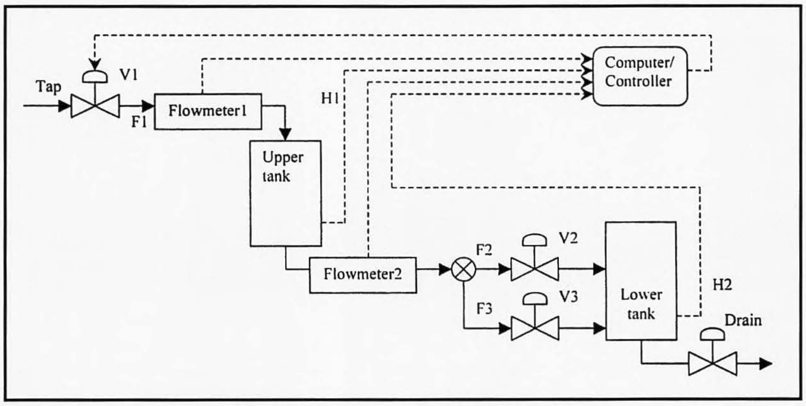

***Figure 3.*** *Interacting water tank-level control.*

❑ ***Single-Tank pH Control*** The objective is to control the pH tank with a continuous flow of acid solution by adjusting the feed rate of a basic solution. The main tank is fed by two peristaltic pumps that draw liquid from two reservoirs, one for acid and one for base. The students do not have access to the flow rate of the acid stream.

The control strategy is to use single-control loop. The acid feed rate is set at 1.8 V. Open-loop responses are implemented by step changing the pump voltage over its full range. The process dynamics of a single pH tank are highly nonlinear, so the model parameters vary significantly as a function of the operating region. For testing closed-loop performances, several PI and PID tunings are used with different set points (pH = 6, 7, and 8). Students observe the varying setpoint tracking performances obtained by different tunings.

Another interesting aspect of this experiment is that the pH probe is located far from the input and output feed streams for the tank and that the mixers are selected to give relatively poor mixing. Because of this, each step response experiment gives slightly different results even when carried out in an identical manner. It is important that students encounter processes that are not completely ideal because this is usually what occurs in practice.

❑ ***Interacting Water Tanks Level Control*** The objective is to control the liquid level in the second of two interacting tanks by adjusting the flow of liquid to the first tank. Water flows from the tap to the pneumatic valve and from the valve into the first tank. From the first tank, the water may flow through either of two valves so that it is possible to choose whether the tanks interact. All levels are measured as pressure differences, which are converted into voltages by transducers (Figure 3).

The preferred control strategy for this experiment is cascade control. Aggressive P or PI tunings are used to control the flow rate in the inner (slave) loop. When the slave loop has been tuned, a second set of process response curves (measuring the level in the second tank with respect to the set point of the inner loop) is constructed. The outer (master) loop is tuned using several PI and PID tunings based on the process parameters obtained. An alternative strategy is to use a simple PID controller that controls the level of the second tank by manipulating the valve voltage. The performance of both strategies can be compared. A goal of this experiment is to recognize the performance improvement obtainable by cascade control.

❑ ***Temperature Control with Variable-Measurement Time Delay*** The objective is to control the temperature at one of several thermocouples downstream from a mixing tank. The manipulated variable is the hot-water feed rate into the mixing tank. A reservoir provides a constant head for a cold-water feed, and a peristaltic pump transfers hot water from a reservoir into the mixing tank. Four thermocouples are located downstream from the outlet of the mixing tank.

Students construct process reaction curves with respect to pump voltage for each of the four thermocouples downstream. They should observe that the time delay in their step responses is greater for thermocouples located further downstream. PI and PID controllers are implemented using each of the thermocouples as the measured variable. Students investigate the effect of changing the time delay on the closed-loop stability and performance by using one thermocouple's tuning rules for the other thermocouples.

❑ ***Integrating Tank-Level Control*** The water level in an integrating tank is the control variable. This tank receives a constant flow of water from the tap. The water level in the tank is measured as a pressure difference signal. Water is removed from the tank by a peristaltic pump under the control of the computer. An interesting feature is that the HP-VEE software assumes that the gain of the process is positive. This would be true if the pump was feeding water into the tank. In the integrating tank, however, the pump drains water away from the tank; therefore, the sign of the controller gain should be negative.

Step changes in the pump voltage are implemented to determine the model parameters, which the students use to tune P, PI, and PID controllers. The integrating characteristics of the tank do not require integral action in the controller to have zero steady-state closed-loop error. Hence, this particular process can be controlled using a single-loop P controller, which can be tuned using direct synthesis. The controller is tuned so that the closed-loop response is as fast as possible, without too much overshoot. Students can test the disturbing response of their controller parameters by implementing the controller under conditions in which the tapwater feed rate changes.

❑ ***Cascade Control of Temperature in a Water Tank*** The objective is to control the temperature in a stirred tank by adjusting a hot-water flow rate. Cold water is supplied to the mixing tank from a reservoir that uses an overflow to maintain a constant level. Hot water flows through a pneumatic valve, and a computer records its temperature and flow rate. The flow rate is measured as a pressure difference across an orifice by a transducer with output in units of volts.

The preferred method is to implement a single cascade loop. Open-loop responses for the flow rate of hot water into the tank are constructed by making a step change in the valve voltage. After determining the gain, time constant, and time delay, students can try several P and PI tunings for the inner (slave) loop to control the flow rate. For tuning the master loop, the steps are the same except that a new set of process response curves is constructed by measuring the temperature of the tank with respect to the set point of the inner loop. Using the same control parameters from the tuning, a single PID controller is implemented and compared with a cascade controller in terms of closed-loop performance.

❑ ***Dye Concentration Control with Load Disturbances*** The objective is to control the dye concentration in a tank under load disturbances by changing the voltage to the feed pump. The 3-liter tank is drained both from the bottom and from an overflow pipe. A pump takes in water from the bottom of the tank and sends it through a colorimeter, which measures the absorbance of the solution using the tap water as a reference, with the outlet of the colorimeter returned to the tank. A peristaltic pump sets the flow rate of dye into the tank (Figure 4).

This process can be controlled using PI or PID control. The absorbance of the solution is measured and compared to a concentration setpoint. The voltage to the dye feed pump is the manipulated variable. Besides determining the setpoint tracking performance, students perform disturbance changes by decreasing the water-feed rate by partially closing the valve at the faucet.

❑ ***4-Tank Water-Level Control*** The objective is to control the water levels in the bottom two tanks (Tanks 1 and 2) with the levels at least two-thirds of the maximum height. On each side, water is pumped upward from a cylindrical beaker and split into two channels at a Y-junction. The relative amount of water entering the two split tubings can be adjusted manually. All liquid levels are measured by pressure transducers. The two pumps adjust the flow of water to the tanks according to voltage signals sent by the PID controllers.

A straightforward control strategy is to use two PID loops to control the process. Both pumps must be calibrated before reliable data can be obtained. By making step changes to the pumps, the process reaction curves for the tank levels are

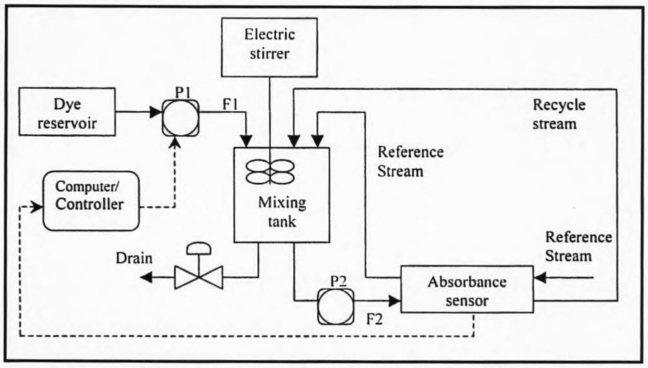

***Figure 4.*** *Dye concentration control with load disturbances.*

obtained. The gains, time constants, and time delays of each process are determined. Each PID loop is tuned separately so that the closed-loop speed of response is as fast as possible, without too much overshoot. After tuning the two single loops, the control loops are implemented simultaneously, and the interactions between the loops are observed. To provide adequate setpoint tracking, the two loops are detuned as necessary.

Decouplers are capable of reducing loop interactions. Students can use the HP-VEE software to implement partial decouplers and assess any improvements/deterioration in the closed-loop performance.

❑ ***Temperature and Level Control in a Water Tank*** The objective is to control the liquid level and temperature in a tank by adjusting the pneumatic valves on hot and cold water feed-flow rates. Both the feed-flow rates and liquid level in the tank are indirectly measured as pressure differences by transducers, which output in units of volts. The presence of two possible actuators suggests the possibility of implementing multiple loops. Since it is possible to receive four measured signals, two cascade-control loops can be used. Students construct process reaction curves for the flow rates into the tank with respect to the voltage sent to the valves. The gain, time constant, and time delay for each of the four transfer functions can then be defined.

The inner (slave) loops should be tuned aggressively without excessive overshoot to control the flow rates. After obtaining good tuning parameters, a second set of process response curves measuring the level and temperature in the tank with respect to the set points of the inner loops is constructed. The process gain, time constant, and time delay for each of the four transfer functions are collected. At this stage, students should be able to assess the level of interaction between the two loops and decide on the pairing. Another possible strategy is to implement two simple PID controllers, control level and temperature, and manipulate the valve voltages. Students can observe and compare the difference in closed-loop performance between the cascade controllers and the PID controllers.

❑ ***Multitank pH Control*** The objective is to control the pH of an acid stream, which flows through three tanks connected in series. This is accomplished by adjusting the feed rates of a basic solution. Three tanks are connected in series. The acid stream enters a pulse dampener before a pH probe measures its pH. The acid stream will enter Tank 1, Tank 2, and Tank 3 before it is drained into a safety reservoir. Each tank has its base flow regulated by one base pump. In addition, a pH probe is located in each tank to measure the pH of the solution (see Ref. 4 for apparatus schematic).

Pumps are calibrated, and their threshold voltages are determined. Step changes should be made in the range bounded by the threshold voltages. The acid flow rate is set throughout the experiment. There are many ways to design a cascade control loop with one master and two slave loops. Yet another way is to implement a full multivariable controller with three inputs and three outputs, and to use partial decoupling followed by multiloop control. Regardless of strategies, students should be able to report any loop interactions. The closed-loop performance is compared with different set points for the third tank (pH = 6, 7, and 8). Since this experiment can be controlled by different strategies, it is especially suited for challenging students to consider and test various control strategies.

❑ ***Integration of Experiments with Control Curriculum*** The control apparatuses, coupled with the use of a HP-VEE as the control software, have been designed to equip seniors with a practical experience in process control. With emphasis on project-based learning, students are given the opportunity to apply theoretical concepts on real industrial processes. They are exposed to the phenomena that limit the achievable closed-loop performance, including process nonlinearity, time delays, disturbances, measurement noise, valve hysteresis, and loop interactions. This provides them with experience in handling real physical systems and practice in applying theoretical concepts to the real process.

Students rated the organization of this course highly but indicated that too much effort was involved in writing the lab report. Based on student feedback over the years, several improvements have been made to the course, including a shorter lab report requirement.

## ACKNOWLEDGMENTS

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