A Process Control Experiment Designed for a Studio Course

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Abstract

A studio-based process control course combines lectures, discussions, simulation exercises and experiments in a single classroom. In this paper we present a chemical process control experiment developed specifically for a studio-based course. The experiment is a simple mixing process involving fresh water and a salt solution. The objective of the experiment is to regulate three measured process variables (level, temperature and conductivity) at desired setpoint values, by manipulating three input variables (freshwater flow rate, concentrated salt solution flow rate and heater power) via feedback control. The experiment is described in detail, and its incorporation into undergraduate and graduate control courses are described.

The Control Studio Concept

During the past decade there has been a major move from a teacher-centered lecture environment to a student-centered learning environment in engineering education. A particular type of student-based learning is the studio approach. In studio teaching an instructor provides motivating mini-lectures, and poses problems to be discussed and solved in class. The instructor serves as the “guide on the side” rather than the “sage on the stage”. A perceived problem with this approach, when computer-based tools are used for problem solving, is that students are often learning how to use software rather than how to formulate and solve engineering problems.

The particular view at Rensselaer is to take the most positive attributes of lectures, simulation-based laboratories and experimental laboratories, and combine them in a single course. Simulation-based assignments have become more common, and are used to illustrate problems that cannot be easily studied using classical pen and paper analytical solutions. Although simulation-based assignments provide much insight to practical control system issues, there is nothing that can take the place of hands-on experiments. To this end, we have developed a control studio that combines lectures, simulation exercises and experiments in a single classroom. Our classroom facility seats 40 students and includes 20 computer-based simulation and control workstations. The students face the front of the studio during lecture and discussion periods, and swivel in their chairs to perform simulations and conduct experiments on the countertops behind them; they work in 2-person teams. During the problem solving periods, the instructor and teaching assistant move around the room answering questions and generating discussion.

The control studio classroom has been used to teach dynamics and control courses in four departments: (i) chemical engineering, (ii) electrical, computer and systems engineering (ECSE), (iii) mechanical engineering, aeronautical engineering and mechanics (MEAEM), and (iv) biomedical engineering. Some of the departments continue to have a traditional control course with separate lectures and laboratory exercises. Chemical engineering was the first department to fully implement a studio-based control course. An overview of the control studio was presented by Bequette et al. (1999).

Learning Modules and Course Projects

A feature of studio-based education is that theoretical principles can be immediately reinforced by practical application examples. We have implemented a number of learning modules as the basis for interactive simulation and discussion. The specific modules used thus far include: (i) SIMULINK tutorial, (ii) PI control of an isothermal reactor, (iii) Internal Model Control (IMC) of an isothermal reactor, (iv) IMC-based PID control of a biochemical reactor (operated at open-loop stable and unstable points), (v) surge vessel level control, (vi) steam drum level control, (vii) anti-windup techniques, and (viii) multiloop control of a distillation column.

The student teams also complete a case study project in multivariable control. They select a unit operation (from a choice of five) to study for the last 1/3 of the semester. The project begins with a literature search, followed by process identification (the process is a masked SIMULINK block diagram) and SISO control system design. The groups then study multiple SISO loops, using RGA analysis and considering failure sensitivity. They write a final report and give an oral presentation. Details are presented in Bequette et al. (1998).

Overview of Experiments

A number of experiments have been developed for use in the studio. Chemical engineering has developed a chemical process control experiment, ECSE has developed a paper winding experiment and MEAEM has developed an electro-mechanical experiment. Each of the experiments can be used in classes taught by the other disciplines. In the sequel we discuss the process control experiment, which will be completely integrated into the process control course in the Spring, 2001 semester.

Chemical Process Control Experiment

The chemical process control experiment, shown in Figure 1, mimics the behavior of a typical chemical process. Fresh feedwater, regulated with a control valve, flows into a vessel containing an electric heater. A concentrated salt solution from a reservoir then mixes with the heated feedwater in a mixing tank that contains a temperature probe. The outlet from the tank discharges through a conductivity sensor into a sink. The objective of the experiment is to regulate three measured process variables (level, temperature and conductivity) at desired setpoint values, by manipulating three input variables (freshwater flow rate, concentrated salt solution flow rate and heater power) via feedback control. The experimental apparatus is benchtop scale (with a “footprint” of roughly 3 square feet), so that it can be used in the studio classroom. The experiment is used at the beginning of the course to motivate students on the importance of feedback control. Students attempt to regulate the three measured outputs manually, by manipulating the three inputs; they find that this is a challenging task since each input affects each output. The experiment is then used to illustrate various modeling, control system design and tuning techniques, culminating in a final design with all control loops closed.

The experiment was designed to have time constants that are roughly 20-30 seconds; the time scale is slow enough for students to observe the physical changes, yet fast enough for a number of experiments to be conducted during an interactive session.

National Instruments hardware and software (LabVIEW) is used for data acquisition and control. The control interface shown in Figure 2 is intuitive, with a simple process and instrumentation diagram that closely matches the experimental apparatus.

The experiment is designed to be used at different points during the course of a semester to highlight topics being covered in the process dynamics and control course. At the start of the semester, when the students do not have much exposure to modeling and control, they attempt to regulate the three measured outputs manually by manipulating the three inputs. The difficulty of this task provides them with motivation to learn to apply feedback control to the process. Once process dynamics and modeling have been covered in the course, the students derive the differential equations that describe the system. These equations are very simple, but obtaining parameter values is challenging. The students also develop empirical models for the input-output relations by performing step tests on the system. The resulting transfer function models obtained will be used to design controllers later in the course.

The students are introduced to control after being taught process dynamics and modeling. PID controllers and their workings are introduced at this point. The students then attempt to control the process using three PID loops without being given any insight into tuning the controllers. It is possible to obtain reasonably good tuning of the PID controllers by trial and error, especially for the level and conductivity loops, but it is a tedious process. The next topic covered in the course is PID tuning. While Ziegler-Nichols and Tyreus-Luyben tuning methods are addressed, the focus is on internal model control (IMC) based tuning of feedback controllers. The students use the models developed earlier to design and tune the PID controllers. If this is done correctly, they should observe improved control performance in all the loops.

Decentralized MIMO control is addressed in the course towards the end, with the emphasis being on deciding input-output pairings using relative gain array (RGA) analysis. For all the earlier control studies, the students have been given a set of input-output pairings. At this stage, the RGA analysis provides them with a confirmation of the choice of those pairings. For this particular experiment, it is easy to pair inputs and outputs based on physical intuition, but the RGA provides a quantitative description of the interaction between the loops. We have decided not to attempt to make the students experts on the use of LabVIEW, so we do not request that they change the loop pairings. Students do learn the effect of different loop pairings via simulation experiments in class, and during their course projects.

In addition to providing students with hands-on experience of modeling and controlling MIMO systems, the experiment exposes them to many practical issues and problems encountered in a real-world application. The inlet flow rate control valve exhibits hysteresis. The experiment is designed to be flow-through with no recirculation using pumps. This is because salt build-up is a distinct possibility with recirculation. During manual control, the on-off heater needs to be monitored and its state changed frequently, since the heater power desired usually lies somewhere in-between its minimum (zero) and maximum values. For automatic control, the control algorithm needs to convert desired heater power into fractions of time that the heater needs to be kept on or off. An important modeling issue while doing step tests is the MIMO aspect of the problem. The input-output relations obtained are dependent on the steady-state values of the other variables at the time of the step test. Performing step tests at one steady state may provide different models from those obtained by performing step tests at other operating points. This provides students with an understanding of interactions in multivariable systems.

We are currently investigating the possibility of placing a flowmeter at the outlet of the mixing tank. This would enable us to demonstrate the concept of cascade control, with the outlet flow rate being cascaded to the level of the fresh water tank, which is then cascaded to the inlet flow rate. A setpoint is specified for the outlet flow rate, and its controller then specifies a setpoint for the tank level controller. The level controller then manipulates the inlet flow control valve. Another possibility is implementing an autotuned control algorithm on this system. Anti-reset windup also needs to be addressed.

A Broader Perspective on Education

It is easy to use this experiment to introduce important automation and control concepts to the general public. In fact, we have used it to provide an interactive learning experience to introduce high school girls to opportunities in engineering and science. The presentation, titled “Order out of Disorder: Controlling Chemical Processes” was used in Rensselaer’s “Design Your Future Day”. In Figure 3, Professor Bequette is shown discussing the experiment with two of the participants. Although these students do not have a process engineering background, they intuitively understand the basic input-output relationships. They quickly turn the experiment into a “video game” where they monitor the three outputs and manually adjust the three inputs. Unlike a video game, however, they can observe what is happening to the physical apparatus. After a while, we place the loops under automatic control, clearly illustrating to the students the importance of automation in chemical process operation.

We are currently extending the experiment for use in graduate control courses, including a course on model predictive control to be taught this fall. The latest release of LabVIEW allows the use of MATLAB files. This will make the development and implementation of advanced control strategies reasonably straightforward. Reports on this experience will also be presented at the meeting.

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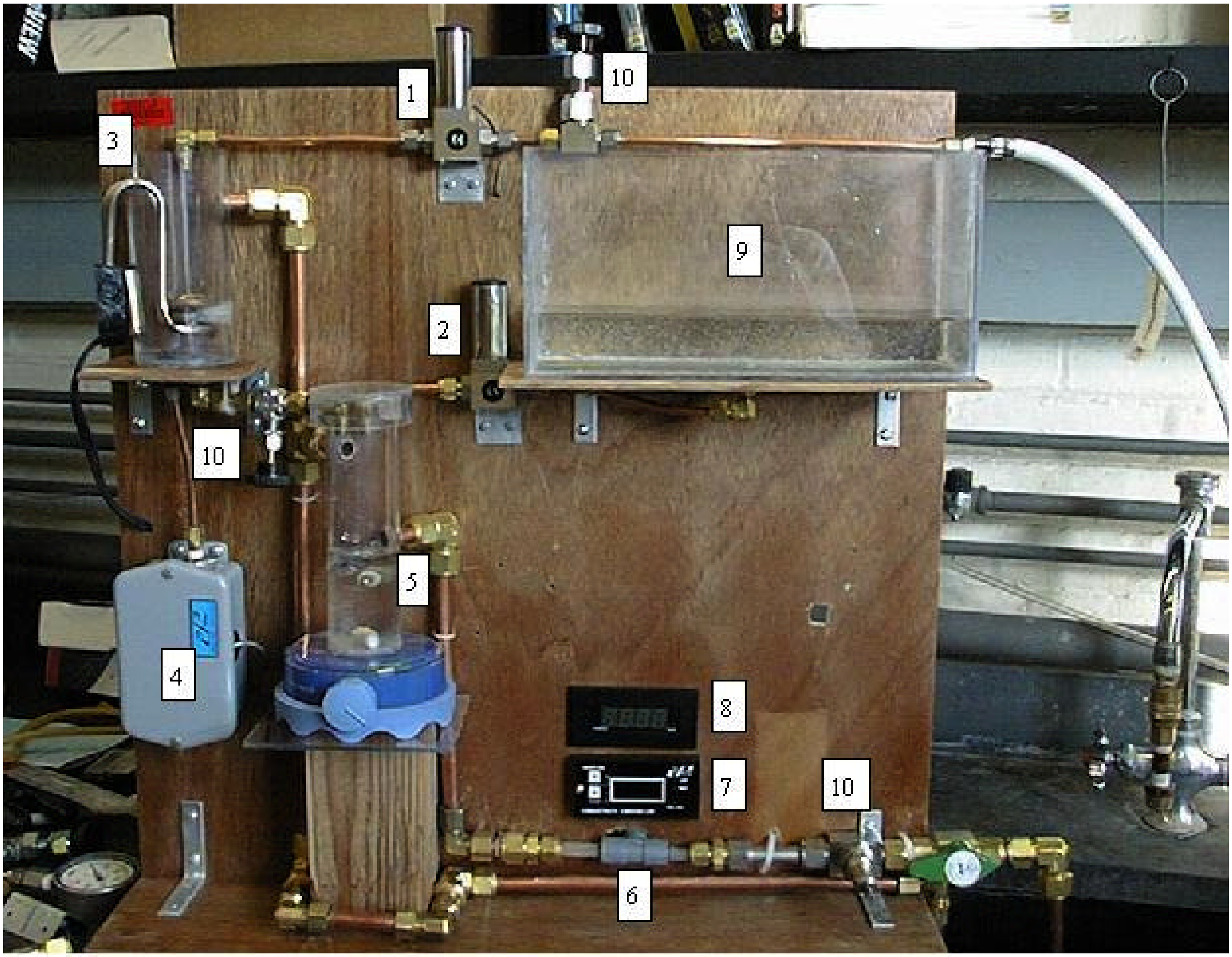

1. Control Valve Fresh Water
2. Control Valve Salt Water
3. Heater for Fresh Water
4. Differential Pressure To Infer Tank Level
5. Temperature Probe In CSTR
6. Inline Conductivity Probe
7. Conductivity Measurement Display
8. Temperature Measurement Display
9. Salt Water Tank
10. Manual Valves For Trimming ΔP

Figure 1. The Chemical Process Control Experiment. Fresh feedwater, regulated with a control valve, flows into the vessel containing an electric heater (upper left). Concentrated salt water, which is regulated with a control valve, then mixes with the heated feedwater in a small mixing tank that contains a temperature probe. The effluent from this tank discharges through a conductivity sensor into the sink.

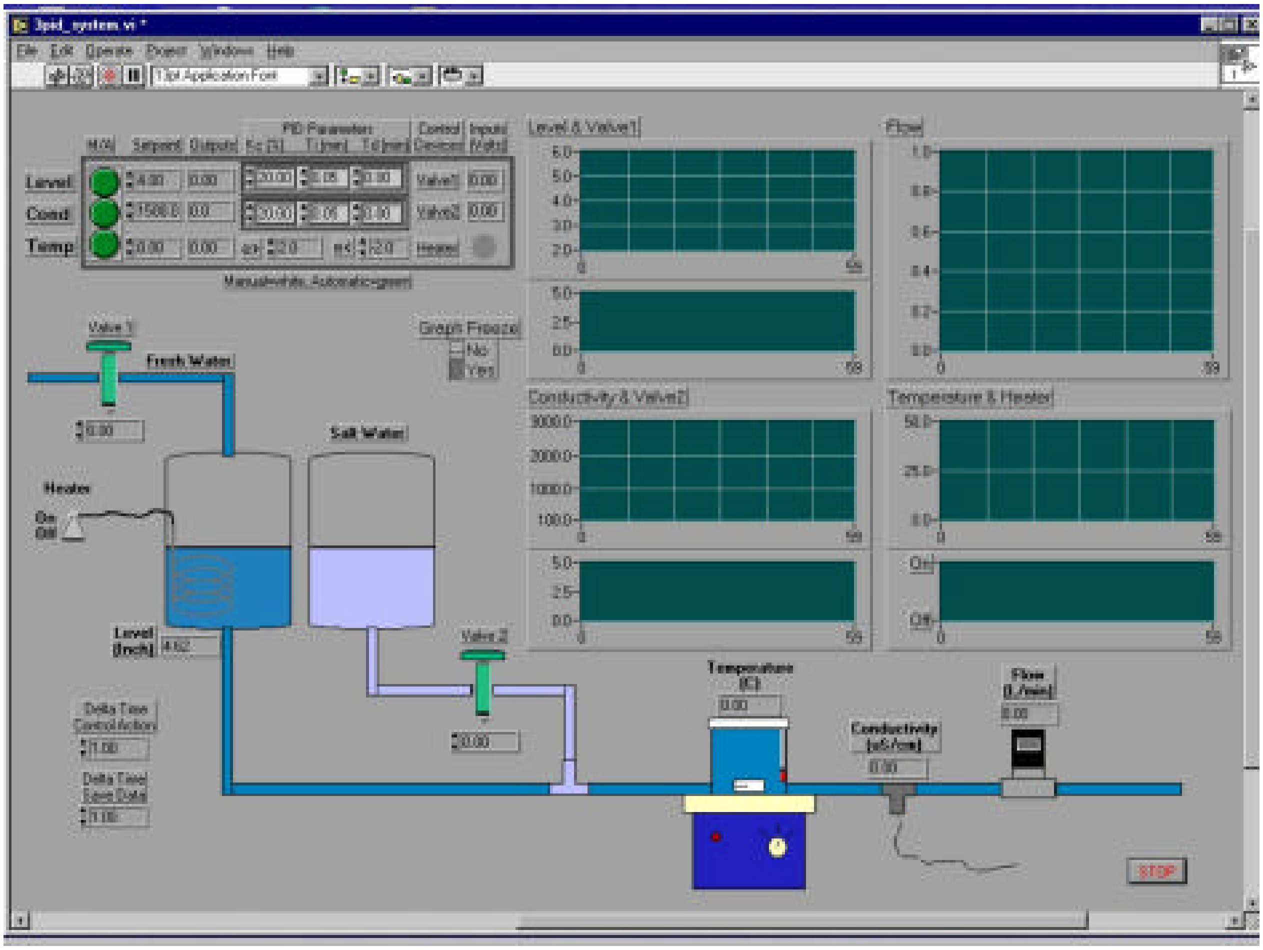

Figure 2. LabView Interface for the Experiment. Each control loop can be placed in either manual or automatic (PID) mode.

Figure 3. Demonstration of the Experiment at Rensselaer's "Design Your Future Day"; an interactive learning experience for high school girls.