CLOSING THE GAP BETWEEN PROCESS CONTROL THEORY AND PRACTICE

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There is increasing pressure on the manufacturing industries around the globe to meet new tougher demands and regulations.[1] Higher product quality, expensive raw materials, larger production volume, environmental and safety regulations, global economy, and other factors have forced industries to rethink the way manufacturing is executed.

Process control or automation is a tool that can be employed by companies to deal with these challenges. Therefore, the demand for people well-educated in process control, especially in chemical-based processes, is increasing. Therefore, universities must also rethink the way process control is taught.

The Experiential Learning[2] theory establishes that learning is a cycle that begins with experience, continues with reflection, and finishes with actions that become concrete experience for reflection. In summary, the learning cycle includes concrete experience, reflective observation, abstract conceptualization, and active experimentation steps, in that order. This means that the learning process is enhanced with hands-on activities[3] in which teams of students[4] act on the fundamentals.

Based on the teaching needs for process control, the Chemical Engineering Department of the University of Puerto Rico at Mayagüez (UPRM) is tackling the challenge of modifying the material taught in the classroom and including hands-on

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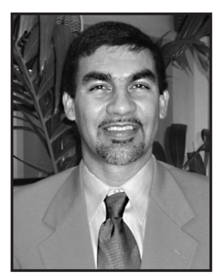

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experience with real industrial control systems and industry practices. The new approach at UPRM integrates process control theory, where all the basic and indispensable concepts and rationale are discussed, with a unique real practice of chemical process control. This paper describes the changes in the course material, the infrastructure to support the innovation, and the hands-on project. The main feature of the project is the use of real industrial technologies and practices to ensure a rookie engineer has a solid basis in process control.

MODIFICATION OF COURSE MATERIAL

A survey of process control course syllabi demonstrates that the typical teaching method used consists of lectures on introduction to process control; principles-based modeling of processes, sensors, and actuators; stability analysis using several techniques; control loop tuning; cascade; feed forward; and maybe an additional strategy if time allows. Most of the process control textbooks are written with a large focus on these topics[5,6] including, in some cases, material related to control practice and standards.

At UPRM, the course has been aligned with a recent trend of several textbooks[7-9] that orient the course toward more practice experience. Table 1 presents the syllabus established to accomplish this alignment; it can be seen that the course starts with control practice topics including laboratory work, real-life example, and seminars offered by an industry expert. This material is followed by a reduced portion of the use of mathematical concepts to support the real application of control. In parallel, the students work in the innovative hands-on experience with an industrial control system (more details ahead).

During the semester the students dedicate 45 hours to classroom time, plus the corresponding time for the exams, plus approximately 35 hours to complete their corresponding tasks for the special project. Therefore, the students dedicate on average eight hours per week to this course, which is taken by the students in their fifth year of the bachelor's degree. This course is taught both Spring and Fall semesters to typically between 45 and 60 students.

The final grade consists of four individual exams (three partials and one final), which have a weight of 75% of the grade. The remaining 25% corresponds to the special project, which most of the time is a group grade. The professor reserves the right to compensate or penalize the student for performance that differs significantly from the rest of the team, however. The objective with the change in material content is to familiarize students with basic experience in most of the

TABLE 1
Organization of Course Topics and Tasks

Hours	Course Topics	Project Tasks (executed out of the class period)
2	Introduction to Process Control	
1		Discussion of project, formation of teams and workgroups
1		Project Management
1	Basic Components of Control Systems - Sensors	Seminar 1: Validation (3 hrs)
2	Basic Components of Control Systems - Actuators	Seminar 2: Distributed Control Systems (3 hrs)
2	Basic Components of Control Systems -Controllers	Preparation and hand-in of Gantt chart (3 hrs)
1	Discrete Control, Boolean Logic	Training with assigned operation and presentation to show how to use the equipment (5 hrs)
1	Control Design (P&ID and SAMA)	
5	Example	
First Partial Exam		
3	Modeling of Dynamic Systems • Balances • Dynamics • Simulation	Progress report by each of the workgroups: process modeling, interface, control algorithm, and validation (5 hrs)
2	Process Parameter Estimation • Hints for experiments	Execution by each workgroup of corresponding tasks. (Industry-expert support is provided) (10 hrs)
3	Design of Single-Loop Feedback Control Systems	Meeting between workgroups and progress evaluators (1 hr)
1	Tuning of Feedback Controllers	Completion of modeling task (5 hrs)
Second Partial Exam		
2	Cascade Control	Completion of interface (5 hrs)
1	Ratio control	Completion of control algorithm and experiments (5 hrs)
2	Feed forward	Completion of validation process and demonstration of performance of the controlled operation (5 hrs)
Third Partial Exam		

The deliverable is a cluster of students aware of the issues of hardware implementation, control strategy selection, and process understanding. Therefore, they are able to contribute more to their employers from Day One of being hired.

issues concerning automating real manufacturing operations but maintaining the basic concepts. Students are exposed to issues such as communication protocols between accessories, integration of software, tuning of real controllers, industry standards, and validation of processes and systems. In the end, the student should be able to connect the control practice with control fundamentals. The deliverable is a cluster of students aware of the issues of hardware implementation, control strategy selection, and process understanding. Therefore, they are able to contribute more to their employers from Day One of being hired—which contrasts sharply with the current situation, in author Velazquez's experience, in which newly hired engineering graduates need from six to 12 months to acquire enough experience to start contributing to companies.

DETAILS ON COURSE MATERIAL

The course begins with students visiting the laboratory to see the industrial control system and the sensors and actuators installed in the different equipment, getting a first-hand view of the control of one of the operations of the industrial control system. The course continues with lectures describing characteristics of sensors, actuators, typical communication protocols, control system specifications, and control strategies. This first section then wraps up with designing control loops (*e.g.*, PID, discrete, dead band) for a chemical process. These control loops are designed and represented through two industry standard formats: one called SAMA (Scientific Apparatus Marketing Association drawings) as well as the well-known Process and Instrumentation Diagram (P&ID).[5] This is the first encounter by students with control loops. The lectures are enhanced with experiences and practical details and aspects of implementation of a process control project from process control engineers. The main idea is to provide students with as much knowledge as possible of real-life applications, such as control logic, for safety of humans and processes. A first individual exam with the same focus as the material covered is administered at this point.

The second part of the semester is focused on the fundamentals of control. The topics include 1) modeling of processes (low-order transfer functions), actuators, and sensors using empirical data; 2) closed-loop transfer function and stability; and 3) tuning. For the modeling of the process including the sensors and actuators, the students perform experiments using the control system, collect the raw data, and fit the low-order transfer functions. For this task, they use the graphical method but they could also use Matlab™ or Excel™. The material offered in the classroom comes directly from the textbook and is enhanced with control practice details especially for the tuning part. This is followed by another individual exam.

The third part then focuses on cascade, feed forward, and ratio control, if time permits. The main idea here is to guide students to learn when and how to implement these strategies to improve the strategies learned before. This objective is basically the same as used in textbooks. A third individual exam is administered after these last topics are covered.

In summary, the students should have learned practical aspects for a process control project, the basic feedback control strategy and its practical aspects, and three additional strategies designed to enhance the basic feedback strategy, all along with the hands-on project.

DESCRIPTION OF THE HANDS-ON PROJECT

The project starts early in the semester by dividing the process control group into five teams. Each team is then subdivided into four working groups. Each working group is then assigned one of four tasks: 1) modeling of the assigned operation; 2) control loop design, implementation, and tuning; 3) control interface; and 3) hardware and software validation. The last two tasks come from the control practice in industry. Each team is provided with a scope-of-work document that describes the project assigned and the objectives, the hardware and software available, and the requirements for grading.

The first task for each team is to use basic project management techniques to prepare a Gantt chart of the remaining tasks to achieve the desired scope, including the overall deadline for the entire project. For this, either the instructor or an expert from the industry (preferred) lectures on project-management basics. Before students start working with the system, additional seminars and workshops are offered in control system configuration and operation and computerized process systems validation. Typically, two or three industry experts help us with the seminars and the direct support to students.

Another requirement is that students must demonstrate to the instructor that they know how to run the particular unit operation and the control system. For this, each team visits the unit operation laboratory and the control room to familiarize themselves with the different accessories, and gather information on how to run their operation.

After that, the group in charge of modeling prepares the procedure to generate and collect the adequate dynamics data for the low-order transfer function. At the same time, the group in charge of control loops designs the different loops through the SAMA drawings and prepares the P&ID drawings. The group in charge of the interface must collect information from the other groups to design the interface. At this point the four working groups must hand in a progress report, which should include the dynamics data and the model of the operation. For the progress as well as the final report, all of the working groups of each team should communicate with each other to ensure each working group has any information required from the other working groups so that the work can be continued and all the details are included in the final report. This interaction is captured in Figure 1.

The project continues with the implementation of the interface and the control loops. During this period, several control experts from local system integration companies coach the students. This approach is similar to the mentoring approach used by Kavanagh and Crosthwaite.[6] Once everything is programmed, the entire group must run experiments in the automated system. The experiments must include at least a step change in set point and one disturbance. The student must characterize the performance of the control system using the standard criteria taught in class such as overshoot and decay ratio.

In parallel, the validation group, which at this point should have prepared the validation document, executes it, collecting data from the other working groups. After this, the four working groups prepare a final collective report that must be handed in by the deadline.

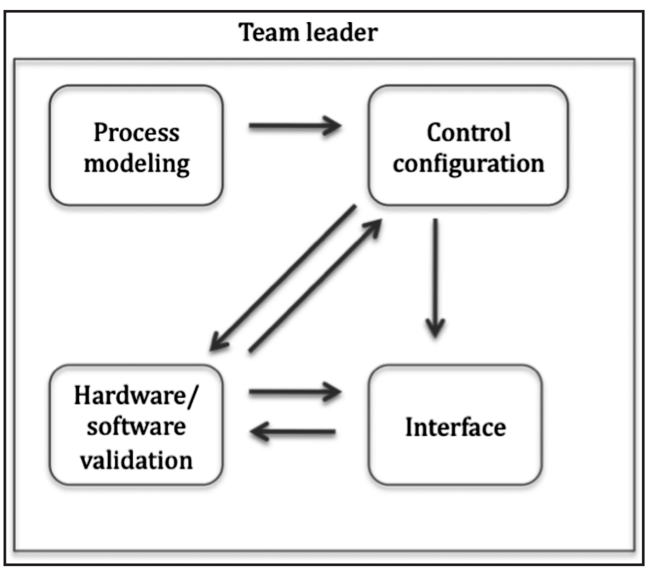

***Figure 1**. Interaction of working groups under the supervision of a team leader.*

The project implementation follows an identical project implementation life cycle to projects currently implemented in industry, to make this experience as valuable as possible. As can be deduced from the above description, the students must employ project-management techniques, prepare progress reports, have project status meeting between the students from each working group and the professors, and in some cases work in interdisciplinary environments.

The interdisciplinary environment is simulated by including in the teams students from electrical engineering who are pursuing a specialization in process control. This experience is typically done only during the Spring semester.

At the project completion, an open house is coordinated sometimes with industry leaders to give the students the opportunity to present and discuss their projects with future employers and professional partners. This exposition to industrial representatives also gives the university an opportunity to get industry feedback in terms of the latest trends and future industrial requirements, in order to continuously focus the projects to fulfill the industrial requirements.

CONTROL TECHNOLOGY AT THE LABORATORY

The infrastructure to support this innovation consists of a control room in the unit operations laboratory, which houses two industrial process control systems identical to the ones currently used in the bulk chemical processing industries. One control system (DeltaV from Emerson Process Management) consists of the controller, a 24V power supply, three analog input cards, one analog output card, one discrete input card, one discrete output card, one fieldbus card, one main administrative computer, and two workstation computers.

The other control system (PCS7 from Siemens) consists of the controllers, the power supply, two analog cards (input, output), and two discrete cards (input, output). This system uses profibus digital communication between the controller and the communication cards.

Five unit operations are connected to the systems: 1) a cooling tower, 2) a chemical reactor, 3) a distillation column, 4) a heated tank and level control, and 5) a heat exchanger. The cooling tower has three industrial pneumatic control valves and a variable frequency driver as actuators. In addition, it has three industrial RTDs (resistance temperature device) to measure the air inlet temperature, the water inlet temperature and the air outlet temperature. With these devices, there are four control loops: 1) air inlet temperature, 2) water inlet temperature, 3) water outlet temperature, and 4) air outlet temperature.

The heated tank and level control apparatus has two control valves, one for water inlet flow rate, and another for steam flow rate. To control the water outlet temperature, the

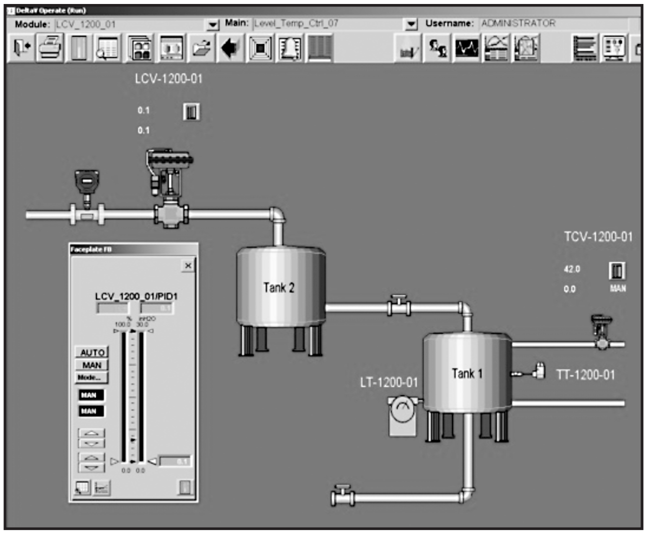

Figure 2. *Example of interface.*

apparatus has an RTD, and for the level it has an industrial pressure cell.

Figure 2 depicts an example of the interface the students developed for the heated tank. They used the symbols provided by the controller software, which are the same they would use or see if they were working in a company.

The heat exchanger also has two industrial pneumatic valves; one for steam flow rate and another for water flow rate. An RTD is installed at the exit of the heat exchanger for the control of the water outlet temperature. An analog flow meter at the entrance is used for the control loop of the water total flow rate through the heat exchanger.

The chemical reactor has two control valves; one is electronic while the other is fieldbus. Each control valve is used to manipulate the flow rate of each of the reactants. In addition, the reactor has four RTDs, two analog flow meters, and an analog pH meter. The pH meter is to control the outlet concentration (conversion) and the flow meters are for the total flow rate (residence time).

The distillation column has two pumps; one for the reflux flow and one for the feed flow. Each of these flows goes through a flow meter. In addition, the column has three control valves; one (fieldbus pneumatic) for the reflux rate, one (electronic) for the feed rate, and one (pneumatic) for the condenser water flow rate. The last actuator is a solid-state relay connected to the heating device of the boiler to manipulate the heat supplied to the solution. The output variables (temperature at the top and bottom plates) are measured with RTDs.

One additional component of the control infrastructure is the software called PI from OSIsoft, which is designed to collect data from industrial control systems. This software allows students to transfer their raw data from the historian of the control systems to spreadsheets like Excel. Once the data is transferred to the spreadsheet, the student can use all of the features of the spreadsheet to compute many different values and prepare plots. The software is installed at a server connected to the university network so that the students can access the data from any computer in the university.

To facilitate the availability of experienced process engineers for class lectures or support, a virtual classroom with videoconference capabilities has been implemented. This permits colleagues from industry to interact with students directly from their respective industrial sites without abandoning their working areas. Students receive the lectures or suggestions in real time and they are able to see, hear, and interact—questioning and clarifying doubts with their virtual professor at their regular class time.

IMPACT ON THE STUDENTS

The course modification was first implemented in Spring 2004 and since then it has transformed approximately 150 chemical engineering and 30 electrical engineering students. Many of these students have used experience from the project in their jobs. In some cases, the students have been the leaders in automation projects of several manufacturing operations (Spring 2008) even as early as in their first six months.

Table 2 presents the average, the maximum, and the minimum of the final grades for the Spring semesters before and after Spring 2004 (when the innovation was first implemented). As can be seen, the semester average after 2004 (75 pts) is 11% higher than the average before 2004. The maximum has increased substantially and the passing percentage has been higher, too. After 2004, withdrawals have been zero, which suggests that the students are more motivated to try until the end even if the grades are not too encouraging.

TABLE 2
Grade Distribution Before and After the Innovation

	Spring 1998	Spring 1999	Spring 2002	Spring 2003	Spring 2004	Spring 2006 I	Spring 2006 II	Spring 2007	Spring 2008
Avg	69.0	52.8	72.6	73.3	65.6	77.8	82.0	71.2	77.0
Max	81.1	89.4	91.9	92.3	81.6	92.0	96.8	95.9	95.0
Min	42.7	17.2	52.1	25.0	21.4	54.5	64.2	52.0	48.0
Pass %	95.0	77.5	87.5	93.1	72.2	88.9	96.9	95.0	90.9
W		4			2				

Looking at the individual exams under the new scheme, however, specifically exams 2 and 3 (related to the understanding of the fundamentals), it can be seen that the students are still earning similar grades as before. The reasons stem from the fact that the change described herein was aimed at modifying the material offered in the classroom and providing the students with hands-on experience with a real industrial control system. Independent of the reason, this provides another opportunity to improve the course once more, by incorporating a strategy to strengthen learning of fundamentals using the very same special project.

During the Spring semester, as mentioned above, students from both departments, electrical and chemical engineering, work together in the project. The dynamics between the students is similar to the one that develops in industry. This interaction helps the students with their interdisciplinary skills, which is one of the outcomes required by ABET (Accreditation Board for Engineering and Technology). Table 3 describes the outcomes that this innovation in process control teaching and learning impacts.

Most of the students do enjoy working with the project and see the value of the approach. Even the teaching of the course is more interesting, from the instructor perspective, especially since it allows the professor to get involved in the project with the students as they develop it during the semester. Many students comment after completing the project that it was a great experience and that they would have preferred to spend more time in the project to go deeper and gain more value out of the experience. Comments from industry professionals are very encouraging and supportive, too. Comments like "Finally, a project that teaches hands-on experience to the students" are heard from them.

The feedback from students has been valuable to keep fine-tuning the changes, including the current scheme of the course. This helps students reduce their initial stress caused by a topic quite different from the core courses of chemical engineering. The students are more motivated to take the course when compared with those that received or are receiving the classical teaching approach.

CONCLUSIONS

The teaching of the course since 2004, although more demanding on the professor, has been more interesting than in previous years. Most of the students enjoy and appreciate the project and most of them improve their opinion about process control as the semester progresses. The industry has been very supportive and consistently has considered the approach very innovative and of positive impact for them.

This approach not only provides practical experience in the process control engineering field but also provides a valuable visualization of the practical applications of all the theory learned. It also stimulates the students to continue with their careers, as there is a direct association of the theory learned and the future use of this knowledge in their professional careers.

The teaching of standards of industrial process control implementation and the experience acquired by implementing the projects complement the theoretical knowledge and help the students visualize and value all the theory learned. Also, the project implementation experience helps students to develop other important skills for their future professional lives, such as: project management, time management, presentation skills, leadership, work under pressure, and documentation and coordination between multidisciplinary groups. This project strongly supports the ABET outcome list.

One issue with the current approach is the time the students spent on the class and the number of credits received. The benefits the students receive, however, especially the solid ground on which to start their careers, outweigh the issue of no proper credit recognition, which can be addressed administratively. Finally, the implementation of the modifications presented here could mean a greater contribution for industry in general and, even more important, for the career of young, new engineers.

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TABLE 3
ABET Outcomes That the New Innovation Impacts

1.	An ability to apply knowledge of mathematics, science, and engineering.
2.	An ability to design and conduct experiments, as well as to analyze and interpret data.
3.	An ability to design a system, component, or process to meet desired needs.
4.	An ability to function in multidisciplinary teams.
5.	An ability to identify, formulate, and solve engineering problems.
6.	An ability to communicate effectively.
7.	Recognition of the need for, and an ability to engage in, lifelong learning.
8.	An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.
9.	Recognition of basic leadership skills.

Automation Technologies, and Invision Engineering in the development of the required infrastructure.

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