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Bridging the Gap between Academia and Industry - Washington University's Process Control Laboratories

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Abstract— **Washington University's Department of Energy, Environmental and Chemical Engineering uses a DCS virtual plant to model and explore bioreactor and bioprocess control opportunities. "State of the Art" industrial software, hardware and novel synthetic biology technologies are utilized to learn actual problems in both traditional chemical plant and new biotechnology industry. Students conduct control concept testing with pilot plant scale hardware/software. Emphasis is placed on advanced control techniques and its new applications that is easy enough to be used by undergraduates with the guidance of an experienced instructor.**

I. Introduction

WASHINGTON University uses molecular biology tools, a bio-reactor and a distributed control system, DCS, to teach undergraduate chemical engineers process control. This paper describes the hardware and software as well as the pedagogy employed. Emphasis is made to educate the students on control techniques employed in industry. Bridging their understanding of control, transport, and unit operations knowledge to laboratory setting does this. The first part of this report will describe the DCS laboratory and the second will describe the bioprocess laboratory.

II. DCS Laboratory Description

A. Hardware and Software

This laboratory consists of a 9.75 m by 5.33 m room and houses 5 control experiments using a state-of-the-art EMERSON DeltaV scaleable distributed control system, DCS with smart transmitters, digital valve positioners, and Fieldbus device network. These instruments and controls are used to control simple processes such as flow, level, pressure and temperature. The scale of the apparatus is comparable to that of a small pilot plant, giving the students a learning environment that closely parallels that of an industrial setting.

The DCS system consists of an industrial electronic controller, an engineering configuration station (a server computer) and four operator/configuration workstations, client computers. All the hardware used in this laboratory is 6 years old. The computers are using current Windows XP operating system and the DeltaV control system is updated as the revisions become available. A local controls system integrator and EMERSON Process Management maintain this system.

Real time process data is available in EXCEL, MATLAB and VisSim Microsoft Windows programs using the OPC standard for industrial computer communications. The students use this interface to build spreadsheets showing unit performance as well as programming dynamic systems that can be controlled using the DeltaV control function blocks.

B. Pedagogy

"*One should not increase, beyond what is necessary, the number of entities required to explain anything*" – William of Occam (c. 1285-1349)

"*Knowing is not enough; we must apply. Willing is not enough; we must do.* "Johann Wolfgang von Goethe (1749 – 1832)

These are the laboratory mottos. The students are encouraged to make their explanations brief and to the point. The laboratory is a dynamic exercise. The students are expected to demonstrate the control behavior. The laboratory allows them to demonstrate a working knowledge of their control skills by building, creating the control strategies and behavior. When the experiment is not working correctly, the students are asked to describe what is wrong, what they believe should be happening. They are asked what choices they can make to correct the problem.

The textbook used in the laboratory is *Principals and Practice of Automatic Process Control*, Third Edition; by Carlos A. Smith and Armando Corripio, John Wiley & Sons, 2006. The text has several references of control strategies that enforce the pre-lab exercises and contain sections on linearization and process time constant calculations. Their discussions on PID behavior and controller tuning is very readable and supports tuning methods used in industry. The text also has good discussions on basic hardware used in the laboratory.

Emphasis in this laboratory course is the industrial application of control techniques that are taught on a basic control theory class. It is expected that the student had completed one semester of basic control theory and a course in unit operations. Most of the students are in their senior year.

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The students work the experiments in groups. They are also encouraged to work their homework and pre-lab assignments as a group. Working in a group helps prepare them for the workplace, since most engineers work in teams or groups. It is preferred to keep the group size to three. Students are encouraged to rotate among themselves to "drive" the workstation configuration task. The hardware layout and the configuration workstation screens are wide enough to permit three students to work the assignments comfortably.

The teaching method incorporated in this laboratory setting is to have the student connect their theoretical modeling transport skills to a setting that mirrors an industrial plant. They are required to calculate the process dynamics as a pre-lab exercise. As an example, for the level experiment, they are required to write a differential equation and solve how long it takes to drain the tank. Once the student has an understanding of the dynamics, they then are taught how to tune the controllers and compensating functions. In addition to the dynamic system calculations, they are also asked to develop control strategies around the experiment. This is added by lecture, examples from the text as well as use of the DCS help files. Throughout the laboratory exercises the instructor has added sections that describe examples of these control techniques in industry. This builds the "bridge" between academic setting and the actual physical industrial hardware and software. As part of the lecture they are instructed in "rules of thumb" and some shortcut methods used industry. For controller tuning, the students learn and use Ziegler-Nichols and lambda methods. The students use the DCS auto tuner and compare their calculated setting to those provided by the tuner. The tuner also provides them with the time constants for the loop. This is done to connect their understanding of theory to actual practice.

To help the students become familiar with an industrial DCS system such as DeltaV, several tutorial exercises is available. Those are used to help the student navigate through the tasks. These show them how to make changes to the control strategy. These are presentations (Power Point) that are several screen shots detailing how they manipulate the configuration tasks in DeltaV.

One of the challenging issues with the laboratory is teaching students from different disciplines. The chemical engineering students are familiar with the laboratory hardware while electrical and mechanical engineers are not. Brief fundamental lectures are delivered that show the basic operation of the unit operations controlled. These lectures are targeted for the specific hardware in the laboratory.

The students do no graphic work with the DCS. They do not physically or electrically add or remove hardware. It is thought that this would be better delegated to technicians rather than engineers.

C. Experiments

Experiment 1, Flow, Level and Pressure Control

This experiment consists of a fully instrumented transparent tank, 0.01 cubic meters with level transmitter and water flow controller and an air pressure controller.

For the pre-lab work, students write a differential equation to simulate the level dynamics as well as calculate the pressure time constant.

This apparatus is used to teach practical aspects of level flow and gas pressure controls. The students begin by developing a proportional only level control and note the offset between the set point and the level signal. Then they add reset and observe the reset correction. Cascade loops are introduced in this exercise be cascading the level controller to the inlet flow controller. A flow, level override control strategy is also taught with this apparatus.

Fig. 1. Experiment 1, flow, level and pressure control.

For pressure controller experiment, the students observe the control behavior with their calculated settings as well as run the auto tuner that provides the students with the process time constants. They then compare these setting with those calculated, providing closure between theory and practice.

Experiment 2, Heat Exchange, Temperature Control

A shell and tube heat exchanger with an area of 0.66 square meters is equipped with hot and cold-water flow controllers as well as temperature measurements on all inlet and outlet streams. Hot water, piped to the tube side, is cooled to a lower temperature by heat exchange with cold water piped to the shell. The student uses this apparatus to learn temperature control fundamentals. A 6-meter length of tubing in piped to the tempered water outlet and a second temperature element is piped at the end. This is used to demonstrate the effect of additional dead time. The students are asked to design a feed forward lead-lag block to compensate for changes in the hot water load. Another part of this exercise is for the students to change PID controller types from real to ideal or series.

The pre-lab exercise consists of presenting the students with a heat exchanger duty sizing program output at various loads. The students then calculate the process time constants and dead times. Since real time process data is available in EXCEL through OPC, the students use this interface to calculate the exchanger heat performance.

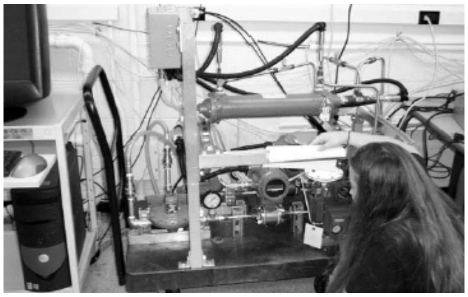

Fig. 2. Shell and tube heat exchanger experiment.

Experiment 3, Liquid flow header control

This apparatus consists of a liquid (water) pressure controller the outlet of which is branched to two flow control loops. This is used to teach liquid pressure control as well as demonstrate control interaction. The control strategy is changed to operate both valves from one flow controller, teaching an example of split range. Then the controls are configured to operate one flow controller as a ratio control to the other. Using a method of controlling the valve position of the furthest open valve by controlling the system pressure also uses this equipment to teach control techniques to implement energy conservation. This exercise acts as a lead in to a discussion on using variable speed pump motor drives as an energy savings technique. The students are instructed on the affinity law and how to calculate savings using this method.

Experiment 4, Discrete Batch Control

This experiment uses a 0.075 cubic meter transparent tank with hot and cold-water flow controlled inlets. The tank has a level transmitter to inventory the contents. An automated agitator is also employed. A discrete controlled drain valve and pump empty the tank. This experiment is used to teach basic sequence control. The students program the distributed control system to perform to a set of defined operating sequences using ANSI-S88 function sequence charts. The

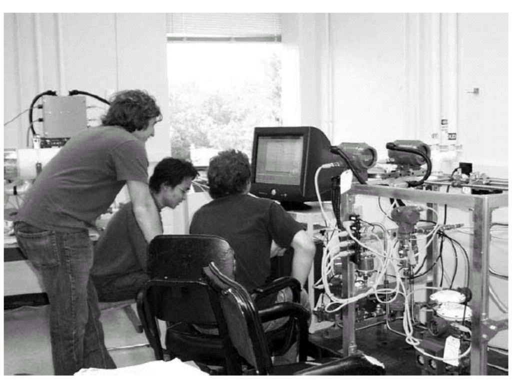

Fig. 3. Liquid flow header experiment.

students are lectured on the basics of batch processes, structured in the standard. As an introduction, they work a simple tutorial problem. Then the experiment in divided into two teams, one builds a sequence to fill the tank as well as turn on the agitator, the second team is assigned the draining exercise. This is done to show how a task can be subdivided into teams. In addition to interacting within their specific group, they now have to assign spokesperson to coordinate between the teams.

Batch processes are frequently used in industry and this gives the students an exposure to control techniques in that control mode.

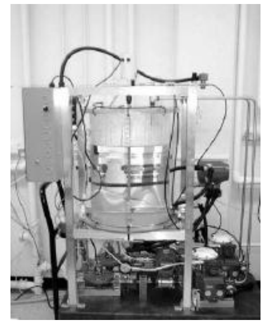

Fig. 4. Discrete batch control experiment.

Experiment 5, Dryer Control

This experiment consists of a horizontal tubular dryer with a rotating screen. 20 wet corks are dried be passing hot air across the rotating screen. An electrical heater using a power controller to control the inlet temperature heats the air. The outlet air temperature and humidity are also measured.

This experiment is used to provide practical application of gas temperature control as well as experimental determination of transport kinetics. The kinetics time constants found by experiment are compared to calculated values.

Two other experiments are constructed as simulations within the DCS system itself. One is on distributed controls systems, also called non-minimum phase processes. They calculate process time constants and configure an external reset controller. This controller is used to show the effects of adding a delay block before the reset integral to minimize overshoot. The other experiment is used to teach nonlinear control. A simulated dead band function block is added to the tank flow control valve to simulate a valve with faulty coupling. This demonstrates a limit cycle with the resulting level control. The students are asked to calculate the describing function and plot that together with the frequency response on a Nichols chart.

In addition to these experiments, the students also are assigned a special project. These involve developing a control strategy based on a published article or a section in the text not previously assigned. The special project may use the MATLAB OPC interface. In those cases, the student uses the MATLAB to write a dynamic simulation of a process. The control is executed in DeltaV. The students then present the results of their experiment to the class in a formal Power Point presentation.

III. THE BIOPROCESS LABORATORY

A) Control theory and new applications in bioprocess engineering

1. Bioreactor control and modeling

Industrial biotechnology often use microorganisms and enzyme catalysts to synthesize useful products and for wastewater treatment. The benefits of biological reactions in large quantities cannot be realized without using process control and optimization theory. The critical frontiers for bioprocess engineering students are direct experience with bioreactor operations and the modeling of dynamic behavior of metabolic reactions under controlled variables. Bioreactor control and modeling must rely on fundamental knowledge in biology, chemistry, mathematics, kinetics, and chemical process engineering. For example, control of bioreactors requires a model to precisely describe biological processes and predict regulatory phenomena. In this section, we discuss the education effort in helping student deal with diverse microbial processes with the process control class at Washington University. We will cultivate a unique learning environment to highlight the integration of control theory and experiments, i.e., combine process control class with the model-based control of bioreactor projects.

2. Experiment: *Saccharomyces cerevisiae* fermentation for ethanol production

The feed-batch operation is used to manufacture ethanol using *Saccharomyces cerevisiae* as a host (Figure 5). The purpose will be to build a bridge between dynamical modeling described in the process control textbook [1] and industrial operations. Specifically, the dynamic model (modified from the text book) will be derived based on the following assumptions: glucose can be converted to ethanol, and ethanol production depends on glucose and oxygen concentrations in the bioreactors. Thereby, standard reaction rate expressions to describe the rate of cell growth with a single limiting carbon substrate are:

Cells: $$\frac{d(XV)}{dt} = V\mu_{\max} X \frac{S}{S+K_S}\frac{[O]}{K_O+[O]} \quad (1)$$

Ethanol: $$\frac{d(PV)}{dt} = VX\frac{S}{\frac{[O]}{K_I}+S+K_S} \quad (2)$$

Substrate: $$\frac{d(SV)}{dt} = FS_f - Y_{S/X}\frac{d(XV)}{dt} - Y_{S/P}\frac{d(PV)}{dt} \quad (3)$$

Overall mass balance: $$\frac{dV}{dt} = F \quad (4)$$

Where X is the biomass, V is the reaction volume, t is time, S is the glucose concentration in the reactor, P is the ethanol concentration, [O] is the oxygen concentration, K_S is the Monod constant, Ys/x and Ys/p are yield coefficients for glucose and ethanol. F is the dilution rate and S_f is the glucose concentration in the feed. Since high oxygen level inhibits ethanol production, we introduce an inhibition coefficient K_I. By controlling the glucose concentration in the feed, dilution rate, and dissolved oxygen (via adjusting air supply rate), ethanol production can be optimized. Student projects use MATLAB and Simulink software to fit the measured data to parameters in the governing equations, and they can then solve the model equations and make the prediction for the final ethanol yield under specified conditions.

Fig. 5: Fed batch ethanol fermentation and control

B) Control theory and new applications in novel biotechnologies

1. Synthetic biology and iGEM team

Synthetic biology is a new area of bioprocess research that combines molecular biology and engineering in order to build novel biological systems and make critical molecules in a cost-effective manner. For example, concerns about global warming and energy independence have intensified interest in biofuels produced via microbial processes [2], i.e., produce biodiesels in a microorganism by introducing the appropriate biosynthetic and tailoring enzymes. Washington University has introduced synthetic biology in the bioprocess class and teaching laboratories, which provides students a great opportunity to learn the knowledge of engineered biological systems and their applications in biosensor, chemical synthesis, human health, and environmental engineering. In 2009, Professor Blankenship and Professor Tang lead iGEM undergraduate programs in synthetic biology and technologies at Washington University.

iGEM is an international arena where student teams compete to design and assemble engineered machines using advanced genetic components and technologies (http://parts2.mit.edu/wiki/index.php/Main_Page). The iGEM competition facilitates this by providing a library of standardized parts (BioBricks) to students, and students can use them to design and build genetic machines. The iGEM project enables the systematic engineering of biology and promotes the open and transparent development of tools for engineering biology; thereby, its influence has been growing exponentially since its first competition in 2004. Table 1 below shows the growth of iGEM society (http://www.the-scientist.com/article/display/55378/).

Table 1: Summary of iGEM society in last five years

Year	No of Team	No of Countries	Winning Team	Projects
2004	5	1	All	Participation
2005	13	4	All	Participation
2006	35	13	Slovenia	A device encoding a feedback loop on the toll-like receptor pathway that dampens the overactive immune response
2007	54	19	Peking Univ.	A device consisting of a spatial and temporal switch controlling bacterial differentiation
2008	84	21	Slovenia	A synthetic vaccine for Helicobacter

The iGEM team (2009) at Washington University includes about 10 undergraduate students from the Departments of Chemical Engineering, Biomedical Engineering, Biology, and Electrical and Systems Engineering. The specific goal of iGEM projects focuses on CO2 sequestration and biofuel production by re-programming the pathways of photosynthetic microorganisms. Students will conduct their projects mainly during the summer under two postdoctoral mentors who will provide direct guidelines for their projects. Students learn engineering approaches and molecular biology tools to organize, model, and assemble complex systems.

2. Control Theory and Systems biology

The ability to manipulate microbial metabolism requires a systems-level understanding of metabolism (systems biology) [3]. Methods in systems biology in a complex metabolic network include: the study of genome sequences and annotation, gene expression using DNA microarrays, proteomics and metabolite analysis, and cell-wide flux analysis. The complexity of cellular regulation poses a great challenge for students to predict the key gene targets for manipulation. The integration of knowledge from engineering disciplines, in particular control theory to biology, may not only advance our scientific understanding of cellular metabolism but also lead to novel technologies. Therefore, our newly designed bioprocess engineering class (for senior students and first year graduate students in chemical engineering and biomedical engineering) will include sections on systems biology.

There are four levels of systems biology and its application in biotechnology. The first step is to study how genes regulate and classify a set of gene operons which control the targeted bio synthesis purpose. The second step is to design the plasmid containing the desired DNA materials and then transform it into cell. The third step is to induce the new gene function and monitor cells' bioproduct synthesis. The fourth step is to optimize the yield of construct and find out the construct (i.e., engineered strain) with the highest yield. The new constructed strain can be analyzed using systems biology tools to further improve its productivity. The final goal is to find the best construct for industrial applications. Below is the diagram of the approach integrating bioprocess, synthetic biology and systems biology (Figure 6). Students in the bioprocess engineering class will learn how to use bioinformatics software and online data base (www.microbesonline.org) to analyze biological systems from different levels. The class targets to integrate computational laboratories in systems biology with synthetic biology tools and large-scale industrial biotechnology.

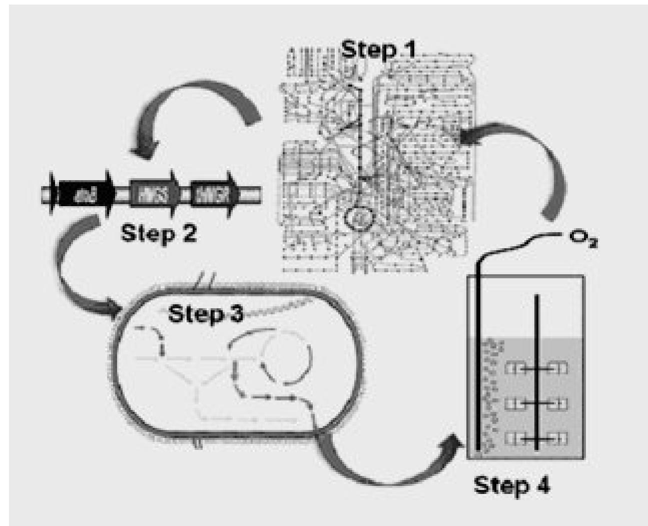

Fig. 6. The pathway from synthetic biology to bioprocess engineering. Step 1. metabolic network analysis; Step 2. gene design; Step 3. engineered cell for biosynthesis; Step 4. overproduction using bioreactor (The figure above is based on Jay Keasling's presentation at the University of California, Berkeley)

IV. SUMMARY

This paper introduces the process control education at Washington University. In order to bridge the gap between academia and industry, the Department of Energy, Environmental and Chemical Engineering has launched a number of programs that foster education on advanced control theory for both undergraduates and graduates. Besides the existing process control courses, the department also has interdisciplinary training of undergraduate and graduate students in synthetic and systems biology-related fields. These programs offer students great opportunities for learning advanced control theory and skills, and thus students can be successful in both academia and industry.

REFERENCES

[1] D.E. Seborg, T.F. Edgar and D.A.Mellichamp, Process Dynamics and Control. 2nd edition. Danvers: John Wiley & Sons, pp41-42. 2004.

[2] J.D. Keasling. Synthetic biology for synthetic chemistry, ACS Chem Biol., vol. 18, 3(1), pp 64-76. 2008

[3] J.D. Keasling. Synthetic biology for synthetic chemistry, ACS Chem Biol., vol. 18, 3(1), pp 64-76. 2008