COUPLED-TANKS LEVEL CONTROL: AN EFFECTIVE COURSE PROJECT AND ITS SOFTWARE DESIGN

Jianchu Yao and Loren Limberis
Department of Engineering,
East Carolina University

Abstract

This paper presents the development of a coupled-tanks level control project and its software design. The project consists of five consecutive laboratory activities that cover the entire process of sensor and actuator calibration, industrial process modeling, controller design, system integration, and system performance evaluation. The project has been administered three times to junior students in a general engineering program. End-of-course survey results show that this design project serves as an effective tool to connect control concepts to a real-life application example. Evaluative feedback from the students reveals that the project possesses features that motivate student learning and improve learning outcomes. The paper emphasizes the LabVIEW software design for this control project including the front panel and the diagram of the digital controller.

Introduction

Control of coupled tank levels is found in many industrial processes in the pharmaceutical and chemical-related industry. To obtain a constant supply flow from a second tank to a bioreactor, for example, a first tank is usually used to remove possible upstream flow variations [1]. Finding and developing effective modeling theory and control schemes has become increasingly attractive to many researchers over the past few years [2-7]. A number of modeling approaches have been explored [7-9]. For example, Rehan et al started with the basic thermal-fluid laws (e.g., Bernoulli's law) to model the process with thermal loss and pump delay considered but not included in the model [8]; Fernandes et al. used differential equations to describe the input-output relationship [7] with only the flow balance of the tanks considered; and Sultan et al. provided the system model in the discrete form, which can be readily realized in digital controllers [9]. Various advanced algorithms, including sliding mode control [2], neural network control [4], and fractional-order proportional integral control [3], have been investigated in 2008 alone.

The broad industrial applications, along with its physical characteristics, make coupled-tanks apparatuses ideal for education purposes to teach controls-related topics, such as: dynamic system modeling, control algorithm design, system specifications, stability, parameter tuning, etc. Engineering educators have recognized these opportunities since the early 1990's. They have used coupled-tanks laboratories to authenticate control theory, deepen student understanding, sharpen their hands-on skills, and promote their enthusiasm for the engineering profession. Among these efforts, Wellstead utilized a scaled model of coupled tanks in their control laboratories [10]. Grega et al. developed a laboratory activity to teach control design, in which the system utilized an IBM/AT computer running DOS as the controller [1]. This experimental setup could also support other concepts, such as digital filtering, A/D and D/A conversion, signal transmission, and sensor calibration. Other educators attempted to take advantage of the Internet connectivity to extend laboratories to non-traditional settings where otherwise laboratories would not be possible due to physical and geographical limitations [11, 12].

Although the current literature supports that coupled-tanks related projects are utilized successfully in engineering education, most of these efforts were designed in curricula within the context of traditional electrical or

mechanical engineering programs. For many other engineering programs, such as general engineering (GE), their curricula do not usually allow thorough coverage of the techniques for system modeling and control (e.g., state space modeling, Z-transform, etc.), yet still require their students to have knowledge of industrial processes and to be able design control systems for these processes.

This paper presents the development of a series of laboratory activities designed around a LabVIEW-based level controller for a couple-tanks apparatus. The laboratory series aims to providing GE students experience of industrial plant modeling, sensor and actuator calibration, digital controller design, and system performance testing. The paper is not intended to reiterate the modeling and algorithm design aspects of the laboratory, as they can be conveniently found in existing literatures [2, 8, 9, 11-14]. It instead focuses on the design of the LabVIEW software used in the laboratory and discusses several practical issues observed during our experiments. The entire project is briefly introduced just to provide the context. More detailed information about the project (e.g., student assignment, project assessment, etc) may be found in [14].

Theory

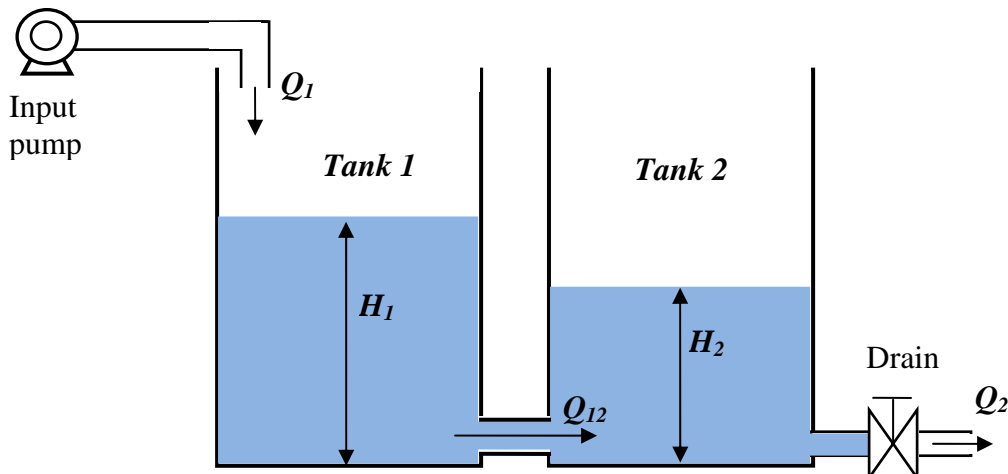Figure 1 illustrates the schematic model of a couple tank apparatus. Water is first pumped into tank 1 by a variable speed electric pump, then flows from tank 1 into tank 2 through an orifice that connects the two tanks at the bottom, and finally runs out of tank 2 through a drain. The input pump, the inter-tank orifice, and the outlet drain tap govern the flow rates Q_1, Q_{12}, and Q_2 and subsequently determine the water levels H_1 and H_2 in the two tanks. The goal is to control tank 2 water level by adjusting the input flow rate of the input pump.

Transfer Function of the Plant:

If assuming the two tanks are identical and their cross section is constant, the system can be modeled with a 2nd-order transfer function [15]:

$$G_p(s) = \frac{H_2(s)}{Q_1(s)} = \frac{1/n}{(1 + sT_1)(1 + sT_2)} \quad (1)$$

where $H_2(s)$ is the tank 2 level, $Q_1(s)$ is the flow rate into tank, and the time constants T_1 and T_2 are determined by:

$$T_1 T_2 = \frac{A^2}{mn} \quad \text{and} \quad T_1 + T_2 = \frac{A(2m + n)}{mn} \quad (2)$$

where A is the cross-sectional area of the tanks, and m and n are further given by:

$$m = \frac{c_1 a_1 \sqrt{2g}}{\sqrt{H_1 - H_2}} \quad \text{and} \quad n = \frac{c_2 a_2 \sqrt{2g}}{\sqrt{H_2 - H_3}} \quad (3)$$

Figure 1. A coupled-tanks system.

where:

c_1 = discharge coefficients of the orifice between the two tanks;

c_2 = discharge coefficients of the drain tap;

a_1 = cross sectional area of the inter-tank orifice;

a_2 = cross sectional area of the drain tap;

H_1 and H_2 = steady state levels in tank 1 and tank 2, for a given input flow rate;

H_3 = height of the drain tap from the bottom of the tanks;

g = gravitational constant (386.22 inch/second^2);

In these equations, the tank levels (H_1 and H_2) can be measured with sensors; the other symbols represent the system constants. Note that, since it is usually very difficult to separate the cross sectional area of the inter-tank orifice a_1 and the drain tap opening area a_2 and their discharge coefficients c_1 and c_2, the products c_1a_1 and c_2a_2 are used as single quantities, which can be obtained from system dynamic response experiments [14].

Desired Closed-Loop Transfer Function:

If a 2nd-order closed-loop system is desired, its transfer function $G_{cl}(s)$ can be represented in a form as shown in the following equation:

$$G_{cl}(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{4}$$

where ζ is the closed-loop system damping ratio and ω_n is the natural frequency.

The parameters used to measure dynamic system performance, which usually include performance measures such as rising time (T_{r1}), percentage overshoot ($P.O.$), and settling time (T_s), can be represented in terms of ζ and ω_n [16], as shown in equations (5) - (7):

$$T_{r1} = \frac{2.16\zeta + 0.6}{\omega_n} \tag{5}$$

$$P.O. = 100\ e^{-\pi\zeta\sqrt{1-\zeta}} \tag{6}$$

$$T_s = \frac{4}{\zeta\omega_n}. \tag{7}$$

Once the system performance requirements are specified, the damping ratio ζ and natural frequency ω_n can be found analytically with these equations. The desired closed-loop transfer function can subsequently be found with equation (4).

The Controller Transfer Function

Once the plant transfer function $G_p(s)$ and the desired closed-loop transfer function $G_{cl}(s)$ are determined, the controller's transfer function $G_c(s)$ can be readily found by:

$$G_c(s) = \frac{G_{cl}(s)}{(1 - G_{cl}(s))G_p(s)} \tag{8}$$

This *s*-domain transfer function needs to be converted into a difference equation that can be implemented as a digital controller. The difference equation takes the form of:

$$\begin{aligned} Q_1 = k_1e(n) + k_2e(n-1) + k_3e(n-2) + \\ k_4Q_1(n-1) + k_5Q_1(n-2) \end{aligned} \tag{9}$$

where:

Q_1: flow rate to be determined by the controller;

$e(n)$: deviation of level 2 from the present sample cycle;

$e(n-1)$: deviation of level 2 from the previous sample cycle;

$e(n-2)$: deviation of level 2 from the sample cycle before the previous;

$Q_1(n-1)$: flow rate of the previous sample cycle;

$Q_1(n-2)$: flow rate of the sample cycle before the previous;

$k_1, k_2, k_3, k_4,$ and k_5: control coefficients.

Project Development

Project Overview

Figure 2 illustrates the setup of the coupled-tanks level control design project, including: the LabVIEW controller on a laptop, the NI ELVIS station, and the coupled-tanks apparatus. The functions of each are briefly described in the text boxes in the figure. In this setup, the project utilizes a PP-100 coupled-tanks apparatus manufactured by KentRidge Instruments [13]. The system uses a personal computer with LabVIEW as the controller. A PCMCIA, multifunction input/output card (DAQCard^{TM}-6062E) from National Instruments is supplied with the computer. This multifunction card has sixteen 12-bit analog-to-digital conversion channels and two 12-bit digital-to-analog output channels.

The project is divided into five lab sessions as listed below. Detailed description of the individual activities could be found in [14].

1. Calibrate the level sensors and the pump: The students experimentally determine the voltage-level relationship of the level sensors and the voltage-flow rate relationship of the pump. These relationships are fitted with appropriate linear models (polynomials) and programmed into LabVIEW.

2. Model the coupled-tanks process with a transfer function: The students conduct a dynamic response experiment to mathematically obtain c_1a_1 and c_2a_2 and find the plant transfer function $G_p(s)$ using equations (1), (2), and (3).

3. Obtain the closed-loop transfer function: The students use equations (2) through (7) to find the desired closed-loop transfer function $G_{cl}(s)$ from the system performance specifications provided by the instructor.

4. Determine the controller's transfer function: The students find $G_c(s)$ with equation (8) and convert it into a difference equation with provided MATLAB code.

LabVIEW Controller: Receives the tank level signals and computes via the digital controller to find the voltage output to the pump.

NI ELVIS Station: Connects the DAQ card and the Kentridge apparatus.

Level Sensors

Pump

Reservoir

Coupled-tanks Apparatus: The two level sensors measure the tank levels and the pump adjusts the input flow to ensure tank 2 reaches the set level.
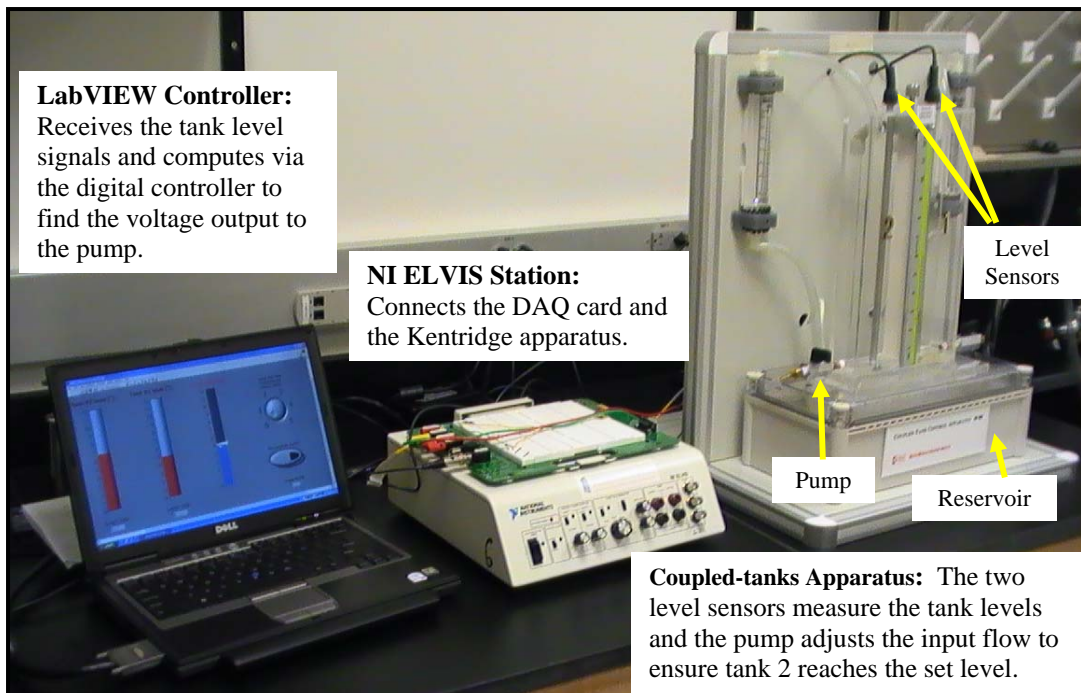
Figure 2. The integrated experimental setup.

5. Integrate the designed controller with the coupled-tanks apparatus: The students program the collected calibration data (for level sensors and pump) and the designed controller into a provided LabVIEW controller template (detailed next); Step-input and impulse-disturbance response experiments are conducted and the students evaluate and analyze the system performance with respect to the provided specifications.

LabVIEW Controller Design

After the process of modeling the plant and designing the controller, a LabVIEW controller template is developed for the students' use in their experiment. Several practical issues deserve attention to make the program better suited to student learning needs. Specifically, the software should:

- Allow adjustment of set levels and display dynamic level changes;
- Allow input of control coefficients (k_1, k_2, k_3, k_4, and k_5 in difference equation (9)) and help students understand the theory behind the equation;
- Sample the tank levels and adjust the pump speed at an appropriate sampling rate;
- Support both manual adjustment of the variable speed pump (MAN) and automatic control of the tank level (AUTO) and seamlessly switch between the two control modes (AUTO/MAN)
- Record data in an appropriate format for students to conveniently analyze the data

The following paragraphs describe the front panel and the diagram of the LabVIEW controller template and explain how the designed software meets the above considerations.

LabVIEW Front Panel:

The front panel (Figure 3) consists of graphical components in two categories: operational controls and graphical indicators.

The operational controls include a sliding control ① that sets the desired tank 2 level, a knob ② that allows manual adjustment of the pump speed, a switch ③ that changes the control modes (AUTO/MAN), a switch ④ to start recording measured data into a spreadsheet file, and a "STOP" button ⑤ to terminate the controller. The graphical indicators ⑥ and ⑦ display the two tank levels. To ease the student learning, graphical components were well organized and labeled. Colors were used to help students differentiate component functions, system status, and operation modes.

LabVIEW Program Diagram:

The diagram of the LabVIEW program (Figure 4) provides all the logic and calculations involved in the application. A "while-loop" structure is used in the program to realize periodic sampling and control of the coupled-tanks apparatus. The system is set to sample and control every 2 seconds to satisfy the Nyquist sampling theorem, since the plant usually has time constants in the range of 30~200 seconds [3, 10]. According to their functions, the diagram can be largely divided into five parts (see Figure 4):

1. Analog Input: This is the front end of the signal flow where the two tank level signals are read into the computer from the data acquisition card. The "DAQ Assistant" module was set to sample every 0.2 seconds. Possible noise is filtered by taking the arithmetic average of every 10 samples (resulting in an overall sampling period of 2 seconds as stated earlier).
2. Level Calibration and Display: The two level signals (voltage) are converted to real level quantities (in inches) using the calibration polynomials obtained from the first lab session. Fourth-order polynomials are currently used, but the order of the polynomials can be easily changed as
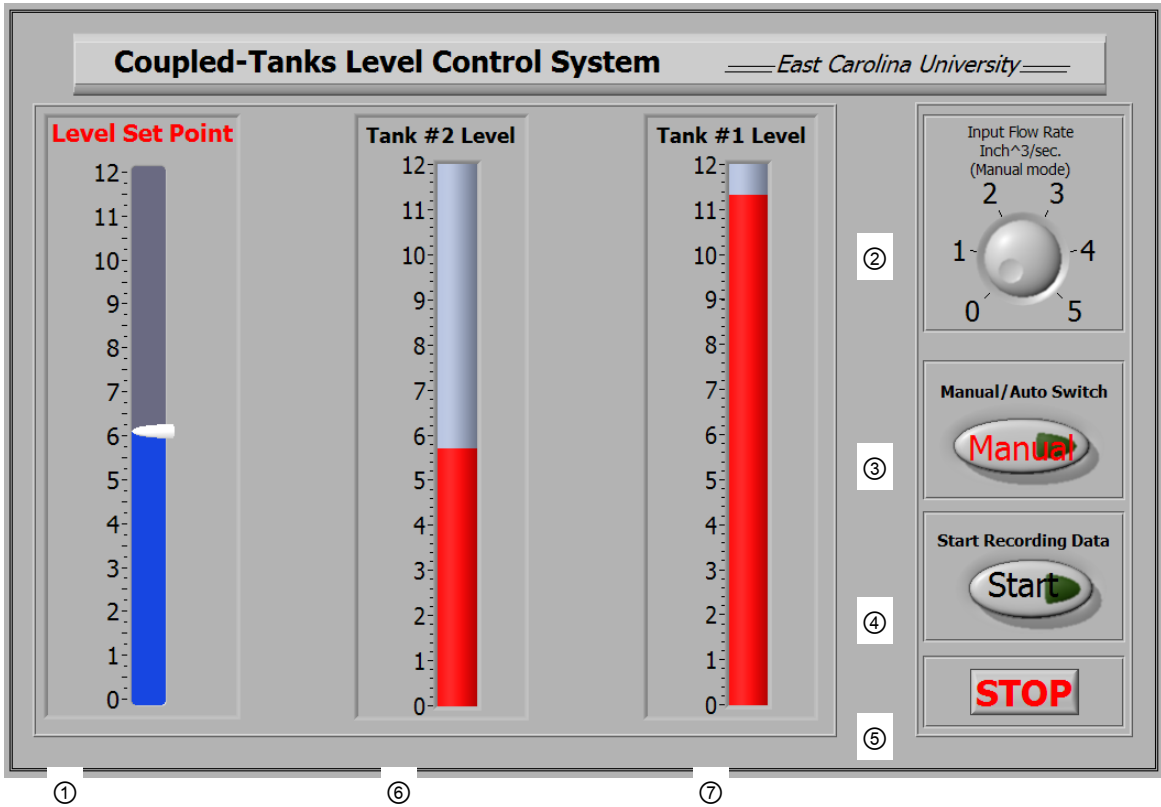
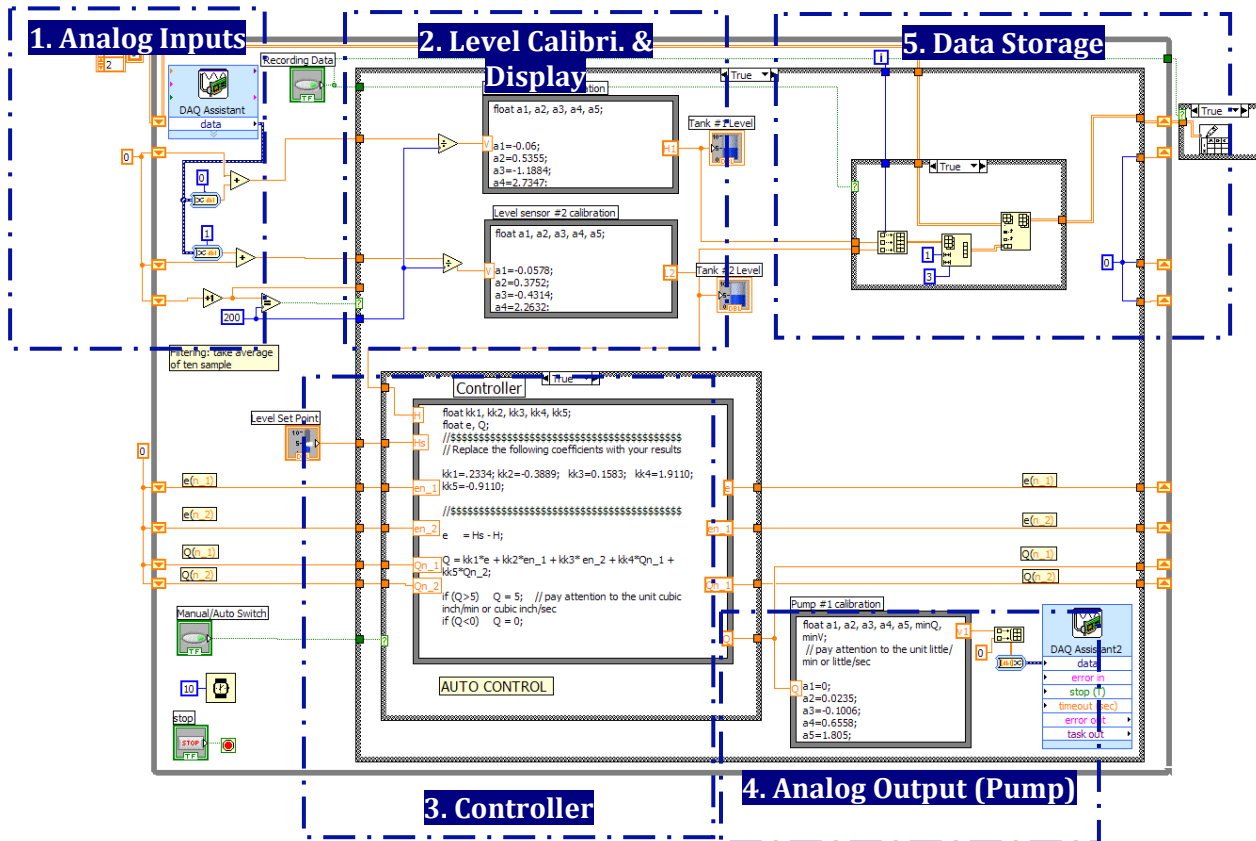Figure 3. The LabVIEW front panel of the level controller.

Figure 4. The LabVIEW diagram of the level controller.

needed. The calibrated levels are displayed in the front panel.

3. Digital Controller: This part implements the controller shown in equation (9). A formula node realizes the difference equation, which first uses placeholders for the control coefficients. Students will replace the placeholders with their control coefficients found from the labs. Shift registers are used to keep data from previous cycles for calculation in the present cycle. One practical issue in this part of the program deserves attention: the calculated controller output (i.e., the liquid flow rate going into tank 1) might be negative, which is obviously not logical. Therefore, the program changes any negative flow rate into zero to better fit the realistic condition.

4. Analog Output: The speed of the pump is adjusted by the voltage signal through the output channel of the DAQ card. The pump calibration data from lab session 1 are used in a formula node to convert the value of the required flow rate from the controller into a corresponding voltage. Note that any unit inconsistencies between plant modeling and pump calibration can be addressed here by introducing a simply conversion equation. Similar to the "Digital Controller", the program ensures the obtained output voltage is within the configured DAQ range. If not, the output voltage will be replaced with the upper or lower voltage limit value to avoid possible false operation.

5. Data Storage: If the "Start" switch for data recording is turned on, the change of the two tank levels with respect to time is saved as three columns in an Excel spreadsheet. The program allows users to select desired file name and path where data are saved. Data can be used to analyze the system performance. Figure 5 shows an example that illustrates the step response of tank 2 level after a set point step change of from 4 inches to 6 inches.

The switch between the manual and automatic control modes allows students to manually adjust the pump speed and, therefore, the input flow. This can shorten the waiting time in cases where tank levels have to change significantly making the labs more efficient.

Results

The design laboratory project has been taught three times to undergraduate GE students at East Carolina University. The project was used to connect these control concepts, design and
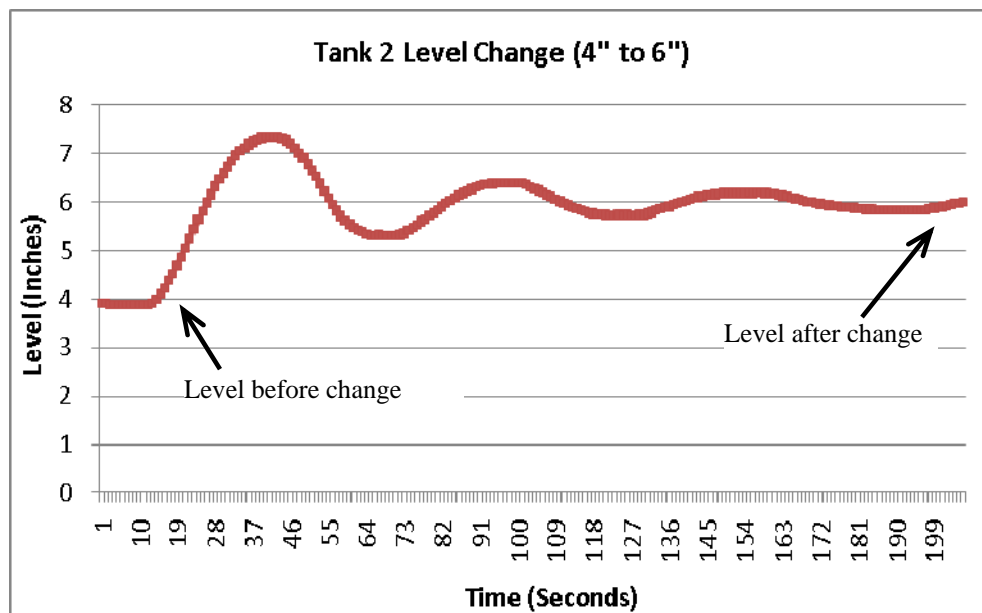

Figure 5. System Step Input Response.

analysis skills, and software tools (MATLABand LabVIEW). Junior engineering students in the ICEE 3050: *Sensors, Measurements, and Controls* class spent five weeks, one activity per week, to design the controllers. Most of the students had some differential equation background but no prior knowledge of controls and system modeling (e.g., Laplace-transform, transfer function, state space).

A five point Likert scale survey (1-Strongly disagree; 2-Disagree; 3-Neutral; 4-Agree; and 5-Strongly agree) was administered at the end of the project to collect students' opinion about the project [14]. The same survey was used in 2007 and 2009. The survey results are summarized in Figure 6. Overall, the average scores for all eight questions are around 4 points, demonstrating that the students were able to achieve all the laboratory objectives. Comparing the results from the two years, however, one may find that most of the questions' responses from 2009 are slightly lower than those from 2007, which is surprising and inconsistent with the instructor's intuitive perception. This may be partially explained by the fact that only 9 out of 25 students in the 2007 class responded to the survey due to some timing issues, while all 18 students from 2009 responded. Nonetheless, the results show that both student groups were very confident about their control system design and analysis skills were improved after the project.

Discussion

Running these three rounds of experiments in the GE program demonstrated that the coupled-tanks level control design laboratory project can serves as a vehicle to facilitate active learning, encourage students to make logical connections between control theory and real world processes, and enhance learning outcomes. The end-of-project surveys indicate that the students appreciated the integration of mathematic models with physical systems and enjoyed the opportunities to acquire hands-on design experience. Although many students expressed that the modeling and design with MATLAB had been challenging and sometimes frustrating due to the fact that they did not have MATLAB background, most of them were excited once they saw the final results from their equations working to control the system. Survey results also showed that the students liked the fact that they could visually observe level changes without the aid of any electronic equipment such as an oscilloscope, since the system time constant is in order of seconds. Many
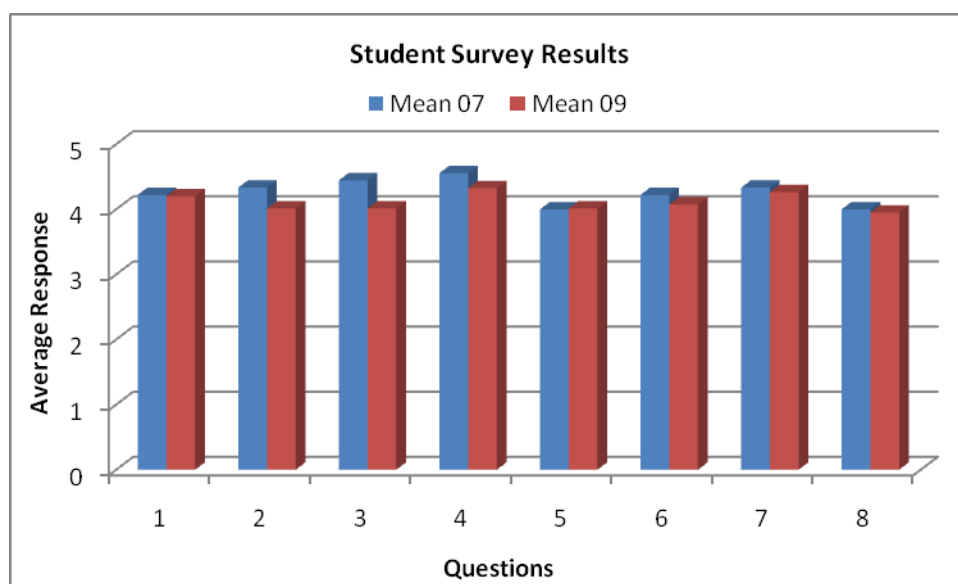

Figure 6. End-of-project Survey Results.

commented that this intuitive visual impact motivated their interests.

In the survey, some students also expressed that they enjoyed using LabVIEW in the project and hoped to have more opportunity to work on LabVIEW programming, which was not surprising. From the student learning perspective, LabVIEW's graphical programming not only makes it easy to understand the signal flow of the controller, it also allows students to develop human-machine interface skills. From a laboratory developer perspective, LabVIEW expedites the teaching tools development without spending significant time on programming, thanks to the existence of powerful functional components for data acquisition, signal processing, and descriptive graphical components. Additionally, a coupled tanks apparatus can be flexibly configured into a 1st-order system with a single tank, a 2nd-order coupled system, a 2nd-order cascaded system, or multiple-input-multiple-output system, [13]. This configuration flexibility improves the equipment's cost efficiency.

During the past three years, a few practical logistic issues that may negatively affect the project progress have been observed. Prior awareness of these concerns can allow one to prepare accordingly, which should prevent occurrence of the following incidents: (1) students occasionally found level sensor readings from later lab sessions inconsistent with previous sessions and had to re-calibrate the sensors due to the poor repeatability of some capacitive level sensors. Keeping one or two spare stations may rescue the teaching plan in case the equipment does not cooperate; (2) the pump, because it has to overcome a head pressure, does not produce any flow when the given voltage is lower than 2 volts. It is important for the students to account for this deadband in their pump calibration; and (3) given the fact that later activities, e.g., controller design, are built upon the success of the earlier ones (modeling of the plant), it is vital for the instructor to be able check the students'

intermediate results. However, this proved to be difficult: the discharge condition and the opening of the inter-tank orifice and drain valve are not directly measurable and may vary significantly from apparatus to apparatus, which in turn results in substantial variations in the obtained plant transfer function. It usually requires the instructor to go through all the steps with several apparatuses before he or she can make knowledgeable decisions when helping students verify their plant models.

Conclusions

This paper presented a project that helps to teach controls to undergraduate engineering student. The project requires students to go through each individual block of a closed-loop control system and it efficiently ties all the controls concepts, design and analysis skills to a practical example. This paper has detailed the development of the LabVIEW-based digital controller used in the project. The features of the graphical programming language LabVIEW eases the development of the teaching modules and enhances student learning. Experience from running the project three times in a GE program demonstrates that the integrative project can make teaching-learning process effective and efficient.

Acknowledgement

References

1. W. Grega and A. Maciejczyk, "Digital control of a tank system," *IEEE Transactions on Education,* vol. 37, 271 - 276 1994.

2. S. Aydin and S. Tokat, "Sliding mode control of a coupled tank system with a state varying sliding surface parameter," in *International Workshop on Variable Structure Systems*, 2008, pp. 355 - 360.

3. V. Bhambhani and Y. Chen, "Experimental study of fractional order proportional integral (FOPI) controller for water level control," in *The 47th IEEE Conference on Decision and Control*, 2008, pp. 1791 - 1796.

4. F. Sharifi and M. B. Menhaj, "A nonlinear observer design via differential neural networks for coupled tanks," in *Canadian Conference on Electrical and Computer Engineering*, 2008, pp. 1457 - 1460.

5. P. E. M. Almeida, F. Goncalves Jota, and C. Seixas Filho, "A novel real time integrated environment for the design of practical fuzzy logic controllers," in *Proceedings of Second International Conference on Knowledge-Based Intelligent Electronic Systems*, 1998 pp. 155 - 164.

6. W. Grega, "Minimum-time liquid level control," in *Proceedings of the Third IEEE Conference on Control Applications*, 1994, pp. 793 - 794.

7. J. M. Fernandes, C. E. de Souza, and G. C. Goodwin, "An Application of Adaptive Scheme to Fluid Level Control," in *American Control Conference*, 1989 pp. 1886 - 1891

8. M. Rehan, F. Tahir, N. Iqbal, and G. Mustafa, "Modeling, Simulation and Decentralized Control of a Nonlinear Coupled Tank System," in *Second International Conference on Electrical Engineering* 2008.

9. A. S. Thulkarmine, M. R. A. Ghani, S. M. Amin, and A. W. I. M. Hashim, "Self-tuning Controllers for a Coupled Tank Pilot Plant: Evaluation and Comparison," in *Canadian Conference on Electrical and Computer Engineering*, 1993, pp. 578 - 581.

10. P. E. Wellstead, "Teaching Control with Laboratory Scale Models," *IEEE Transactions on Education,* vol. 33, pp. 285-290, AUGUST 1990.

11. C. C. Ko, B. M. Chen, J. Chen, Y. Zhuang, and K. Chen Tan, "Development of a web-based laboratory for control experiments on a coupled tank apparatus," *IEEE Transactions on Education,* vol. 44, pp. 76 - 86, Feb 2001

12. R. Irawan, M. Ooi, G. Yeung, E. Weyer, D. Nesic, and I. Mareels, "A virtual laboratory experience based on a double tank apparatus," in *Proceedings of the 40th IEEE Conference on Decision and Control*, 2001, pp. 2815 - 2820.

13. K. K. Sin and K. W. Lim, "APPLICATION EXAMPLES OF THE KRi Coupled-Tank Apparatus PP-100'," K. I. P. Ltd, Ed., 1995.

14. J. Yao and L. Limberis, "A Project-Driven Approach to Teaching Controls in a General Engineering Program," in *2008 Annual American Society of Engineering Education Conference*, Pittsburg, MA, USA, 2008.

15. "Coupled Tanks Systems 1," www.control-systems-principles.co.uk/whitepapers/ coupled-tanks-systems.pdf.

16. R. C. Dorf and R. H. Bishop, *Modern Control Systems*, 10 ed.: Pearson Prentice Hall, 2005.

Biographical Information

Dr. Jianchu (Jason) Yao joined the Department of Engineering at East Carolina University as an Assistant Professor in August, 2005. He received a B.S. and M.S. degrees in electrical engineering from Shaanxi university of Science and Technology, China, in 1992 and 1995, respectively, and the Ph.D. degree in electrical engineering from Kansas State University in 2005. His research interests include wearable medical devices, telehealthcare, bioinstrumentation, control systems, and biosignal processing. His educational research interests are laboratory/project-driven learning and integration of research into undergraduate education. Dr. Yao is a member of the American Society for Engineering Education and a senior member of Institute of Electrical and Electronics Engineers.

Loren Limberis, PhD is an Assistant Professor in the Department of Engineering at East Carolina University. He earned his B.S. in electrical engineering and Ph.D. in bioengineering from the University of Utah. Dr. Limberis was a research analyst with Southwest Research Institute prior to his academic career. His research interests focus on designing techniques to utilize nature's highly complex and sophisticated biological systems to develop biohybrid devices for use in biotechnology applications.