2006-1522: TWO-TANK LIQUID LEVEL CONTROL USING A BASIC STAMP MICROCONTROLLER AND A MATLAB-BASED DATA ACQUISITION AND CONTROL TOOLBOX

Anshuman Panda, Polytechnic University

ANSHUMAN PANDA was born in New Delhi, India. He is currently pursuing a dual B.S/M.S. degree in Electrical Engineering and expects to graduate in December 2006. He is a member of Tau Beta Pi. He has worked as a teaching and research assistant with responsibilities in the area of mechatronics.

Hong Wong, Polytechnic University

HONG WONG was born in Hong Kong, China. In June of 2000 and 2002, he received the B.S. and M.S. degrees, respectively, in Mechanical Engineering from Polytechnic University, Brooklyn, NY. He is a member of Pi Tau Sigma and Tau Beta Pi. He worked for the Air Force Research Laboratories in Dayton, OH, during the summers of 2000 and 2001. He is currently a doctoral student at Polytechnic University. His research interests include control of mechanical and aerospace systems.

Vikram Kapila, Polytechnic University

VIKRAM KAPILA is an Associate Professor of Mechanical Engineering at Polytechnic University, Brooklyn, NY, where he directs an NSF funded Web-Enabled Mechatronics and Process Control Remote Laboratory, an NSF funded Research Experience for Teachers Site in Mechatronics that has been featured on WABC-TV and NY1 News, and an NSF funded GK-12 Fellows project. He has held visiting positions with the Air Force Research Laboratories in Dayton, OH. His research interests are in cooperative control; distributed spacecraft formation control; linear/nonlinear control with applications to robust control, saturation control, and time-delay systems; closed-loop input shaping; spacecraft attitude control; mechatronics; and DSP/PC/microcontroller-based real-time control. He received Polytechnic's 2002 Jacob's Excellence in Education Award and 2003 Distinguished Teacher Award. In 2004, he was selected for a three-year term as a Senior Faculty Fellow of Polytechnic University's Othmer Institute for Interdisciplinary Studies. He has edited one book and published four chapters in edited books, 37 journal articles, and 76 conference papers. He has mentored 67 high school students, 38 high school teachers, 10 undergraduate summer interns, and seven undergraduate capstone-design teams. In addition, he has supervised three M.S. projects, two M.S. thesis, and two Ph.D. dissertations.

Sang-Hoon Lee, Polytechnic University

SANG-HOON LEE was born in Seoul, Korea. He received the B.S. degree in Mechanical Engineering from Sung Kyun Kwan University, Seoul, Korea, in 1996 and the M.S. degree in Mechanical Engineering from Polytechnic University, Brooklyn, NY, in 2002. From 1996 to 1997, he worked for Samsung Engineering Co., Ltd. in Korea. He is currently continuing research at Polytechnic University as a doctoral student. His research interests include linear/nonlinear control and mechatronics.

Two-Tank Liquid Level Control Using a
Basic Stamp Microcontroller and a
Matlab-Based Data Acquisition and Control Toolbox

1. Introduction

A variety of PC-based data acquisition and control (DAC) boards are currently available in the market. These DAC boards can be broadly classified in two categories: *i)* high-end DAC boards, which provide a wide range of advanced hardware capabilities along with a sophisticated software environment, and *ii)* low-end DAC boards, which are primarily used for data acquisition of a few selective signals while using proprietary software.

With the emergence of Matlab[1] as a widely used scientific computing tool in industry and academia, many users seek a DAC platform that can interface with and exploit advanced computing capabilities of Matlab to perform hardware in the loop experiments. Moreover, within the last decade, new developments in automated code generation programs have allowed users to utilize interactive icon-based control system simulation tools such as Simulink[2] for real-time control. In particular, using the Simulink block library and Real-Time-Workshop (RTW) along with Simulink block libraries for vendor-specific DAC boards, one can generate C code from Simulink-based feedback control diagrams for real-time controller implementation on PC-based DAC boards. The ability to rapidly and efficiently design and implement complex control algorithms using an icon-based programming environment enables control designers to enhance productivity.

Unfortunately, the use of Matlab as a software environment for DAC tasks frequently requires the use of expensive DAC boards (over \$1,000) which include advanced hardware features (e.g., high sampling rates and high resolution analog to digital converters) that a typical user may not utilize to the fullest potential. Thus, the use of existing PC-based DAC hardware and software solutions may be uneconomical for certain users (especially educators) interested in designing and building experiments that require a sophisticated software interface with minimal hardware costs.

In contrast to the PC-based DAC boards, microcontrollers are inexpensive devices (costing only a few tens of dollars) which are widely used for embedded computing in hobby, academic, and industrial projects. However, a majority of microcontrollers require programming using one or other embedded programming variants of high-level programming languages (e.g., Basic, C, Java, etc.). In addition, many low-cost microcontrollers do not allow floating-point numerical computations that may be needed to implement advanced feedback control algorithms.

In recent research,[3] we have developed a low-cost DAC platform which allows microcontrollers to be programmed by Matlab and Simulink thus providing an inexpensive tool for data acquisition and control tasks. This platform is well suited for tasks that require graphical user interface and/or advanced computational capabilities, but do not require stringent hardware

performance. It uses the advanced computing power of Matlab, the graphical user interface of Simulink, and Parallax Inc.'s Basic Stamp 2 (BS2) microcontroller[4] to provide an environment which allows users to implement sophisticated control designs using inexpensive hardware. Furthermore, it provides a library of BS2 functions for Simulink, allowing for direct interaction between user-defined Simulink block diagrams and sensors/actuators connected to the BS2.

The framework of reference[3] is significant for several reasons. First, it overcomes the two limitations common to most microcontrollers, *viz.*, the lack of advanced icon-based software interface for efficient development of control algorithms and the lack of a graphical user interface (GUI) to allow intuitive interaction. In particular, our DAC toolbox overcomes these two limitations by extending the capabilities of Simulink to low-cost microcontrollers. Second, our DAC platform is very economical since it requires the use of only an off-the-shelf BS2 microcontroller (under $50) and obviates the need for overhead software such as RTW required for most PC-based DAC systems, thus further lowering the cost of acquiring such a system. This affords an opportunity to students to conduct industry-style rapid control prototyping and hardware in the loop experiments. Third, the ability to interface and program microcontrollers using the intuitive graphical programming environment of Simulink provides the flexibility and versatility of equipping a wide array of undergraduate-level laboratories (physics, measurement systems, feedback control, and mechatronics) at an economical cost using our DAC platform. Fourth, our microcontroller-based DAC system is inherently portable due to its small size and low power requirement, extending its benefits to students who can acquire their personal DAC system for capstone design projects and for experimental research.

In this paper, we illustrate several important features of the aforementioned DAC platform[3] by performing liquid level control of a coupled, two-tank system. Liquid level control is ubiquitous in industrial applications, e.g., food processing, effluent treatment, power generation plants, pharmaceutical industries, water purification systems, and industrial chemical processing. Thus, the study of liquid level control encompasses many engineering disciplines, e.g., electrical, chemical, civil, and mechanical.

In this paper, we employ the classical proportional-plus-integral (PI) controller for liquid level control of a coupled, two tank system.[5] To effectively utilize this control methodology, the system parameters, e.g., tank dimensions and pump characteristics, must be known exactly. However, this may not be feasible since system parameters may change due to the effects of scaling in tanks and orifices, aging of pump, and wear. Thus, to determine the system parameters, we conduct an experimental system identification study which uses the inherent nonlinear dynamics of the two tank system.

This paper is organized as follows. First, in Section 2, we outline the basic features of the Matlab data acquisition and control platform.[3] Next, in Section 3, we describe the coupled, two-tank system model and formulate system identification and control design objectives. In Section 4, we outline a method to perform system identification. In Section 5, we design a PI controller. In Section 6, we perform experimental validation of the results of Sections 4 and 5. Finally, in Section 7, we draw some concluding remarks.

2. Matlab Data Acquisition and Control Platform

In this section, we briefly outline the salient features of a software platform[3] that enables the use of an inexpensive microcontroller such as BS2 for data acquisition and control tasks. This framework allows Matlab and Simulink to seamlessly interact with the BS2 microcontroller; i.e., using the features of Simulink, this software platform allows for *i)* automatic generation of PBasic code (the native programming language for the BS2 microcontroller) for a variety of sensors and actuators that can be connected to the BS2 microcontroller; *ii)* programming of the BS2 microcontroller; and *iii)* data communication between the BS2 microcontroller and Matlab. In particular, this framework provides a library of Simulink functions, which allows for direct interaction between user-defined Simulink block diagrams and sensors/actuators connected to the BS2 microcontroller. See reference[3] for a detailed overview of this software platform.

2.1. Component Overview

The PC-based data acquisition and control platform of reference[3] is composed of two main components, hardware and software. The hardware required for this platform is the BS2 microcontroller and user selectable sensors and actuators. The software required for this platform is Matlab with serial communication capability and Simulink. We refer to the software implementation of this PC-based data acquisition and control platform as the BS2 data acquisition and control toolbox.

The BS2 microcontroller is used as a hardware interface that relays sensor data to and actuator data from a PC. Furthermore, the BS2 microcontroller communicates with the PC using a serial communication port. For further details on the BS2 microcontroller, see the Parallax website.[4]

The BS2 data acquisition and control toolbox supports several different types of input and output signals (see reference[3] for a comprehensive list). However, in this paper, only analog input and output signals between ±5 Volts are considered. To convert an analog input signal to a digital format for use on a PC, we utilize the LTC1296 analog to digital converter (A2D) IC, which is natively supported in the BS2 data acquisition and control toolbox. The LTC1296 A2D IC is a 12-bit A2D and is manufactured by Linear Technology Inc. It can support up to 8 single input channels, which can be used as 4 differential inputs. For additional details on the LTC1296 A2D IC, see website of Linear Technology.[6] Analogously, to convert an actuation signal, whose representation is in a digital format, to an analog output signal, we utilize the MAX537 digital to analog converter (D2A) IC, which is natively supported in the BS2 data acquisition and control toolbox. The MAX537 D2A IC is a 12-bit D2A and is manufactured by Dallas Semiconductor Inc. It can support up to 4 single output channels, which can be used as 2 differential outputs. For additional details on the MAX537 D2A IC, see website of Dallas Semiconductor.[7]

Matlab is the primary software package used in the BS2 data acquisition and control toolbox. In addition to providing functionality for the Simulink toolbox, the Matlab scripting language allows for high level development of functions that can interface with specific hardware, in particular the serial communication port. Reference[3] exploits this capability by using built-in serial communication functions provided by Matlab (supported by versions 6.1 and higher) to communicate data with the BS2 microcontroller. Furthermore, the BS2 data acquisition and

control toolbox utilizes the graphical user interface capabilities of Simulink to allow users to construct block diagrams interfacing with sensors and actuators.

2.2. Simulink Block Diagram Design using BS2 Toolbox Overview

The BS2 data acquisition and control toolbox allows users to implement control designs and to develop data acquisition and control panels within Simulink block diagrams. This toolbox provides a Simulink custom library, which contains blocks that interface with sensors and actuators connected to the BS2. See Figure 1 for a complete listing of sensor and actuator blocks currently available in the BS2 library. To use sensors and actuators available from the BS2 library, users must design a control panel or control algorithm using a predefined, blank, Simulink template model file. The key property of this template model file is the inclusion of functions used to program the BS2 microcontroller just before the Simulink block diagram is executed. When a user saves this model file and runs the Simulink block diagram, a set of predefined operations are initiated before the Simulink block diagram is executed. These operations are as follows:

i) define global variables to initiate serial communication;
ii) generate PBasic code based on the sensor and actuator blocks used in the Simulink block diagram to be excuted on the BS2 microcontroller;
iii) program the BS2 microcontroller via the serial communication port; and
iv) start the Simulink block diagram if the BS2 microcontroller was successfully programmed, otherwise stop the block diagram and display an error message.
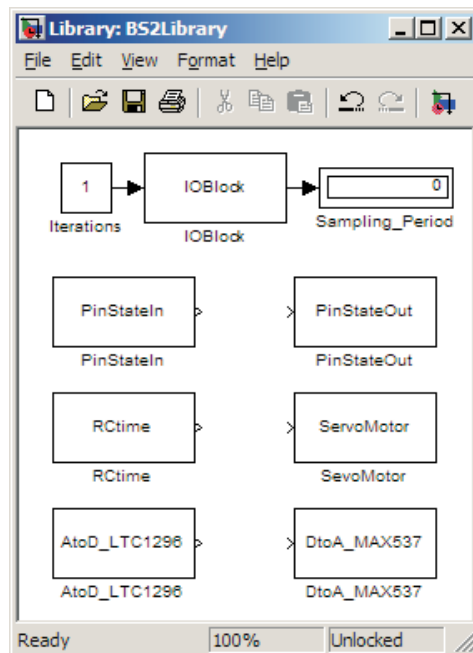

Figure 1: BS2 Sensor and Actuator Block Library

In this paper, we use only the blocks labeled *IOBlock*, *AtoD_LTC1296*, and *DtoA_MAX537* from Figure 1. The following are brief descriptions of these blocks:

IOBlock: The main function of this block is to *i)* initiate serial communication between the BS2 microcontroller and Matlab, *ii)* send and receive data between BS2 and Matlab, and *iii)* terminate this serial communication link. Aside from serial communication, another important task of IOBlock is to provide the sampling period of a given Simulink block diagram. This feature allows blocks that require the sampling period to be used properly, e.g., an integrator block or a timer block (clock). The sampling period is denoted as the amount of time required for one cycle of the Simulink block diagram to execute. The sampling period provided by the IOBlock is an averaged sampling period that is calculated by averaging the time taken to run a specified number of cycles of the Simulink block diagram. The number of cycles used for averaging is user definable, such that the user can adjust the resolution of the sampling period, i.e., a larger number of cycles will provide a finer resolution of the sampling period compared with a smaller number of cycles. However, this procedure of obtaining a sampling period does not provide the exact sampling period for each Simulink block cycle; thus, this BS2 data acquisition and control toolbox does not enforce any real-time requirements, i.e., enforcing a specific sampling period for the Simulink block diagram is not permissible.

AtoD_LTC1296 block: This block receives voltage data from an LTC1296 A2D IC. The LTC1296 A2D IC is a 12-bit A2D (11-bit plus an additional sign bit) that has 8 single input channels, which can be used as 4 differential inputs. Furthermore, this IC is controlled by the BS2 via the serial peripheral interface (SPI).

DtoA_MAX537 block: This block sends voltage data supplied by the Simulink block diagram to the MAX537 D2A IC. The MAX537 D2A IC is a 12-bit D2A (11-bit plus an additional sign bit) that has 4 single output channels, which can be used as 2 differential outputs. Furthermore, this IC is controlled by the BS2 via the serial peripheral interface (SPI).

3. Coupled Two-Tank System Model

The picture in Figure 2 shows a two degree-of-freedom, state-coupled, two-tank system. This system consists of two tanks with orifices and liquid level sensors at the bottom of each tank, a pump, and a liquid basin. The two tanks have the same diameters and can be fitted with differing diameter outflow orifices. In this experimental setup, the pump provides the infeed to Tank 1 and the outflow of Tank 1 becomes the infeed to Tank 2. The outflow of Tank 2 is emptied into the liquid basin. The following conditions, with regard to the system dynamic model, are used to describe the levels of liquid in Tanks 1 and 2:

i) the liquid level in Tanks 1 and 2, denoted as $L_1(t)$ and $L_2(t)$, respectively, are measured using two pressure sensors;
ii) $L_1(t)$ is always greater than 0 cm and less than 30 cm;
iii) $L_2(t)$ is always greater than 0 cm;
iv) the desired liquid level in Tank 2 is greater than 0 cm and less than 20 cm for $t > 0$; and
v) the voltage applied at the input terminals of the pump, denoted by $V_p(t)$, is between 0 and 22 Volts.
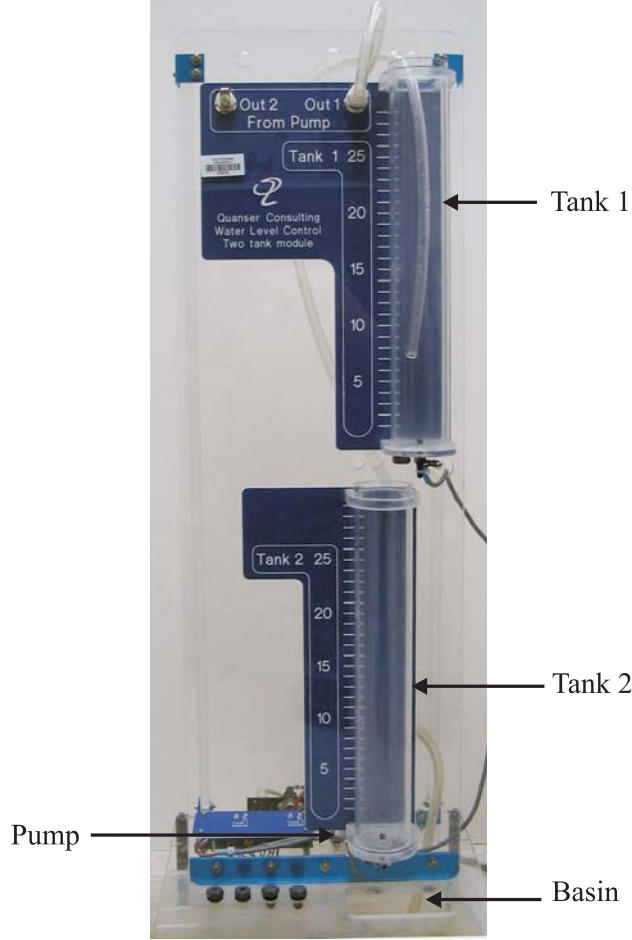
Figure 2: Two Degree-of-Freedom, State-Coupled, Two-Tank System

The nonlinear mathematical model describing the liquid levels of Tanks 1 and 2 is given by[5]

$$\dot{L}_1(t) = -A\sqrt{L_1(t)} + BV_p(t), \tag{3.1}$$

$$\dot{L}_2(t) = C\sqrt{L_1(t)} - D\sqrt{L_2(t)}, \tag{3.2}$$

where $A \triangleq \dfrac{a_1}{A_1}\sqrt{2g}$, $B \triangleq \dfrac{K_p}{A_1}$, $C \triangleq \dfrac{a_1}{A_2}\sqrt{2g}$, and $D \triangleq \dfrac{a_2}{A_2}\sqrt{2g}$, a_i is the cross-sectional area of the outflow orifice at the bottom of the Tank i, A_i is the cross-sectional area of the Tank i, K_p is the pump constant, g is the gravitational acceleration, and $i = 1, 2$.

3.1. System Identification Objectives

In this paper, we assume that the system parameters A, B, C, and D or equivalently a_i, A_i, K_p, and g for $i = 1, 2$, are not known exactly. As previously discussed, the uncertainty about system parameters may arise due to corrosive buildup in the liquid level system or the deterioration of the pump motor. Thus, a control design based on the idealized values of the system parameters may lead to performance deterioration for the closed-loop system. In a

subsequent section, we outline a series of experiments, which exploit the nonlinear dynamics of (3.1) and (3.2), to numerically estimate the system parameters $A, B, C,$ and D.

3.2. Control Objectives

Given a desired, constant, liquid level for Tank 2, denoted as L_{2d}, design a control input $V_p(t)$ such that $\lim_{t \to \infty} L_2(t) = L_{2d}$. This objective is to be achieved with the assumption that $L_1(t)$ and $L_2(t)$ can be measured. Furthermore, the control design is to utilize estimates of the system parameters.

To quantify this control objective, we define the liquid level tracking error for Tanks 1 and 2, i.e., $\ell_1(t)$ and $\ell_2(t)$, as follows:

$$\ell_1(t) \triangleq L_1(t) - L_{1d}, \tag{3.3}$$

$$\ell_2(t) \triangleq L_2(t) - L_{2d}, \tag{3.4}$$

where L_{1d} is some desired, constant liquid level for Tank 1, which using (3.2) is characterized as

$$L_{1d} \triangleq \left(\frac{a_2}{a_1} \right)^2 L_{2d}.$$

3.3. Linearized Error System Model

To facilitate the design of a controller to achieve the aforementioned control objectives, we begin by describing the linearized error system model (see reference[5] for details)

$$\dot{\ell}_1(t) = \alpha_1 \ell_1(t) + \beta_1 u(t), \tag{3.5}$$

$$\dot{\ell}_2(t) = \alpha_2 \ell_2(t) + \beta_2 \ell_1(t), \tag{3.6}$$

where $u(t) \triangleq V_p(t) - V_{pd}$ and V_{pd} is the desired pump voltage, which using (3.1) is characterized as $V_{pd} \triangleq a_1 \frac{\sqrt{2gL_{1d}}}{K_p}$. Furthermore, the parameters $\alpha_1, \beta_1, \alpha_2,$ and β_2 in (3.5)–(3.6) are defined as, respectively,

$$\alpha_1 \triangleq -\frac{A}{\sqrt{4L_{1d}}}, \ \beta_1 \triangleq B, \ \alpha_2 \triangleq -\frac{D}{\sqrt{4L_{2d}}}, \ \text{and} \ \beta_2 \triangleq \frac{C}{\sqrt{4L_{1d}}}. \tag{3.7}$$

Next, we develop the transfer function models for the linearized error system of (3.5)–(3.6) by taking the Laplace transform of (3.5) and (3.6) and rearranging terms to yield

$$\frac{\ell_1(s)}{u(s)} = \frac{\beta_1}{s - \alpha_1}, \tag{3.8}$$

$$\frac{\ell_2(s)}{\ell_1(s)} = \frac{\beta_2}{s - \alpha_2}, \tag{3.9}$$

where $\ell_1(s) \triangleq \mathscr{L}[\ell_1(t)]$, $\ell_2(s) \triangleq \mathscr{L}[\ell_2(t)]$, $u(s) \triangleq \mathscr{L}[u(t)]$ and $\mathscr{L}$ is the Laplace operator.[8]

4. System Identification

In this section, we outline an experimental method to determine the parameters of the coupled two-tank system given in (3.1) and (3.2). Specifically, motivated by the nonlinear dynamics of (3.1) and (3.2), we outline a set of experiments that yield the system parameters $A, B, C,$ and D. In experiment 1, we first obtain numerical values for the ratios A/B and C/D. In experiment 2, we obtain the numerical value for the parameter A, which using the numerical value of A/B obtained in experiment 1 yields B. In experiment 3, we obtain the numerical value for the parameter D using the same procedure as in experiment 2, which using the numerical value of C/D obtained in experiment 1 yields C.

4.1. Experiment 1

In this experiment, we obtain expressions that relate the ratios A/B and C/D to steady state conditions of the pump and the liquid level of Tanks 1 and 2. Specifically, we begin by noting that if a fixed voltage is applied to the pump, then the liquid level of Tanks 1 and 2 will reach steady state after a sufficient amount of time. This characteristic can be proven by directly solving the differential equations (3.1) and (3.2) given that $V_p(t)$ is constant. Next, the solution of (3.1) and (3.2) under steady state conditions, i.e., with $\dot{L}_1(t) = 0$ and $\dot{L}_2(t) = 0$, is given by

$$\frac{A}{B} = \frac{V_{pss}}{\sqrt{L_{1ss}}}, \tag{4.1}$$

$$\frac{C}{D} = \sqrt{\frac{L_{2ss}}{L_{1ss}}}, \tag{4.2}$$

respectively, where $L_{1ss}, L_{2ss}, V_{pss}$ are the steady state liquid level of Tanks 1 and 2, and the steady state pump voltage, respectively. From (4.1) and (4.2), by applying a fixed voltage V_{pss} to the pump and directly measuring the liquid level of Tanks 1 and 2 after a sufficient amount of time, i.e., L_{1ss} and L_{2ss}, we can determine numerical values of A/B and C/D.

4.2. Experiment 2

In this experiment, we fill Tank 1 with a fixed amount of liquid and record the time history of the liquid level in Tank 1 as it is discharged. Using this time history, we can determine a relationship between the system parameter A and the liquid level in Tank 1 at a given time instant. To do so, we solve the differential equation (3.1) with $V_p(t) = 0$ and obtain

$$\sqrt{L_1(t)} = \sqrt{L_1(t_0)} - \frac{1}{2}A(t - t_0), \tag{4.3}$$

where t_0 is the initial time and $L_1(t_0)$ is the initial liquid level in Tank 1. Note that equation (4.3) is only valid when the right hand side of (4.3) is nonnegative, i.e., prior to full discharge of Tank 1 since once Tank 1 is fully discharged the right hand side of (4.3) becomes negative. To

determine when the liquid in Tank 1 is fully discharged, we set $L_1(t) = 0$ in (4.3) and solve for the corresponding time, resulting in

$$t^* = \frac{2\sqrt{L_1(t_0)}}{A} + t_0, \tag{4.4}$$

where t^* is the time of full discharge of Tank 1. Using (4.4), the analytic expression for the liquid level in Tank 1 is given by

$$L_1(t) = \begin{cases} \left(\sqrt{L_1(t_0)} - \frac{1}{2} A(t - t_0) \right)^2 & t < \frac{2\sqrt{L_1(t_0)}}{A} + t_0 \\ 0 & t \geq \frac{2\sqrt{L_1(t_0)}}{A} + t_0 \end{cases} \tag{4.5}$$

Thus, if we choose a time instant $\bar{t}$ with $\bar{t} < \frac{2\sqrt{L_1(t_0)}}{A} + t_0$, or equivalently when the liquid level in Tank 1 is still discharging, then (4.3) can be rewritten to yield the parameter A as follows

$$A = 2\frac{\sqrt{L_1(t_0)} - \sqrt{L_1(\bar{t})}}{(\bar{t} - t_0)}. \tag{4.6}$$

Next, substituting (4.6) into (4.1), we can determine the parameter B as follows

$$B = \left(2\frac{\sqrt{L_1(t_0)} - \sqrt{L_1(\bar{t})}}{(\bar{t} - t_0)} \right) \frac{\sqrt{L_{1ss}}}{V_{pss}}. \tag{4.7}$$

Note that the determination of the numerical value for B in (4.7) requires the use of the experimental data obtained from experiments 1 and 2, i.e., the steady state values L_{1ss}, V_{pss} from experiment 1 and $\bar{t}, t_0, L_1(\bar{t}), L_1(t_0)$ from experiment 2.

4.3. Experiment 3

In this experiment, we fill Tank 2 with a fixed amount of liquid and then obtain the time history of the liquid level in Tank 2 as it is discharging. Using this time history, we can obtain a relationship between the system parameter D and the liquid level in Tank 2 at a given time instant. Similar to experiment 2, using the solution of (3.2), we obtain a relationship between the system parameter D and the liquid level in Tank 2 as follows

$$D = 2\frac{\sqrt{L_2(t_0)} - \sqrt{L_2(\hat{t})}}{(\hat{t} - t_0)}, \tag{4.8}$$

where $\hat{t}$ is a time instant before Tank 2 is fully discharged. Now, substituting (4.8) into (4.2), we can determine the parameter C as follows

$$C = \left(2\frac{\sqrt{L_2(t_0)} - \sqrt{L_2(\hat{t})}}{(\hat{t} - t_0)} \right) \sqrt{\frac{L_{2ss}}{L_{1ss}}}. \tag{4.9}$$

Note that the determination of the numerical value for C in (4.9) requires the use of the experimental data obtained from experiments 1 and 3, i.e., the steady state values L_{1ss}, L_{2ss} from experiment 1 and $\bar{t}, t_0, L_2(\bar{t}), L_2(t_0)$ from experiment 3.

5. Proportional-Plus-Integral (PI) Liquid Level Control

In this section, we outline a PI liquid level control design that is based on the linearized model of (3.8)–(3.9). As described in subsection 3.2, the liquid level control problem consists of controlling the liquid level of Tank 2 to a desired, constant liquid level L_{2d}. From (3.9), to control the liquid level in Tank 2, we must use the liquid level of Tank 1, i.e., $\ell_1(t)$, as a pseudo control input. This necessitates control of liquid level of Tank 1 to a desired liquid level L_{1d}, which serves as a command signal for the Tank 1 controller $u(t)$, or equivalently $V_p(t)$.

Referring to Figures 3 and 4, we design PI controllers for Tank i, $i = 1, 2$, as follows

$$C_i(s) = K_{Pi} + \frac{K_{Ii}}{s},\qquad(5.1)$$

where K_{Pi} is the proportional gain and K_{Ii} is the integral gain. To aid in determining the controller gains K_{Pi} and K_{Ii}, the desired closed-loop responses for Tank i are specified in terms of a settling time T_{si} and percent overshoot o_i performance criterion. It then follows from reference[8] that the settling time and percent overshoot criterion can be related with the closed loop damping ratio ξ_i and natural frequency ω_{ni} for Tank i, as follows

$$\xi_i = \frac{b_i}{\sqrt{b_i^2 + \pi^2}},\qquad(5.2)$$

$$\omega_{ni} = \frac{4}{T_{si}\xi_i},\qquad(5.3)$$

where $b_i = \log\left(\frac{o_i}{100}\right)$. Thus, using (5.2)–(5.3), the controller gains K_{Pi} and K_{Ii} that achieve the desired closed-loop responses for Tank i are obtained as follows[5]

$$K_{Pi} = \frac{1}{\beta_i}\left(2\xi_i\omega_{ni} + \alpha_i\right),\qquad(5.4)$$

$$K_{Ii} = \frac{\omega_{ni}^2}{\beta_i},\qquad(5.5)$$

where α_i and β_i given in (3.7) depend on the parameters A, B, C, D, which are obtained via system identification.

6. Experimental Validation

This example explores the experimental system identification and liquid level control of a two tank, liquid level system using the BS2 microcontroller and the BS2 data acquisition and control toolbox of reference.[3] The two-tank, liquid level system is commercial laboratory equipment developed and marketed by Quanser Consulting Inc.[9]
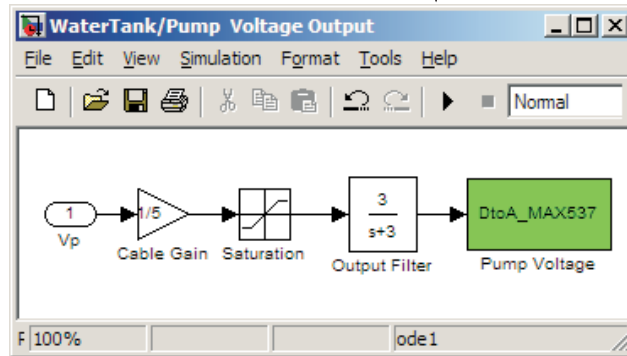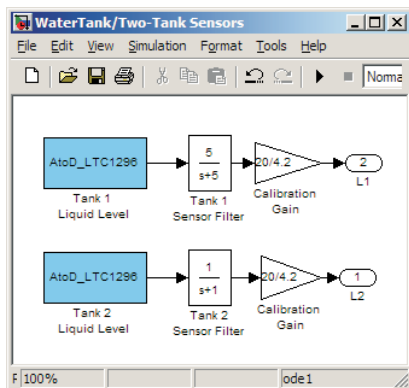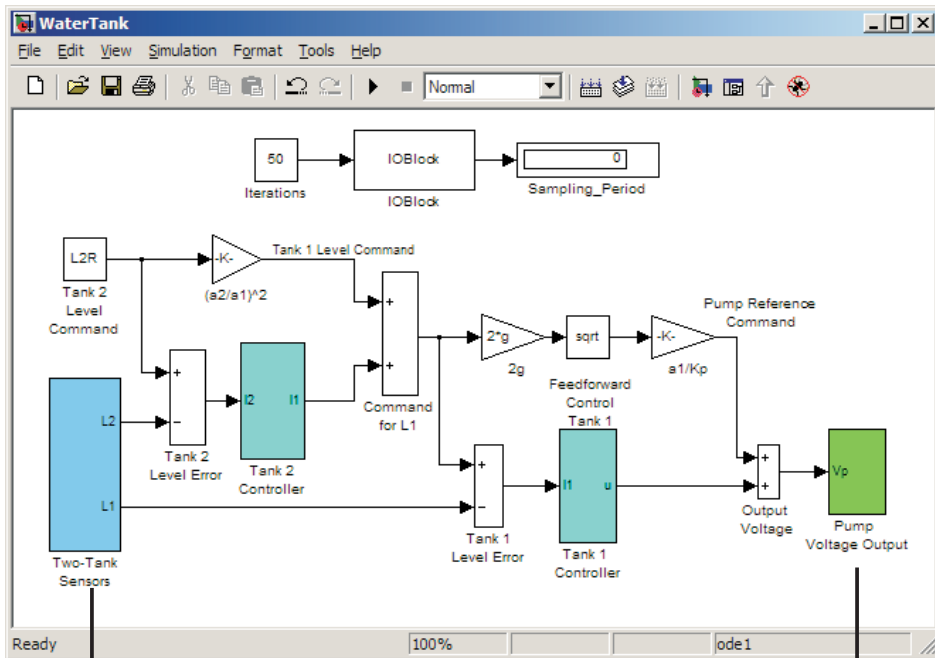
Figure 3: Simulink Block Diagram of the PI Controller for Tanks 1 and 2
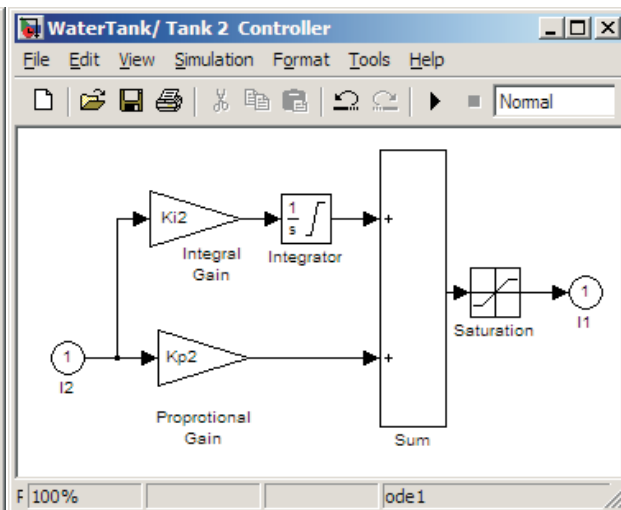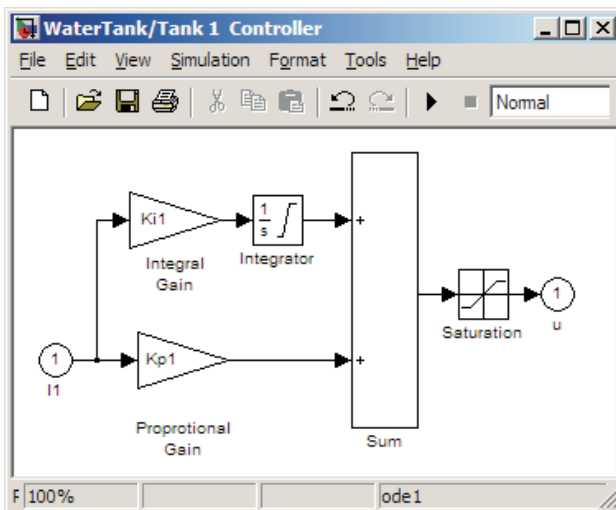

Figure 4: PI Controller for Tanks 1 and 2.

As described in Section 3, the liquid level of Tanks 1 and 2 are measured using a pressure sensor, where the output signal of the sensor is a voltage in the range of 0 to 5 Volts corresponding to the liquid level in Tanks 1 and 2. A calibration gain for the pressure sensors is then determined, i.e., the gain that converts the sensor output voltage to centimeters of liquid is computed as $\frac{20}{4.2}\left(\frac{cm}{Volt}\right)$. The pressure sensor analog signals are supplied to the LTC1296 A2D and are utilized in the Simulink block diagram, as shown in Figures 3 and 5. Using the MAX537 D2A, the BS2 supplies a controlled voltage signal to the pump, which controls the liquid level of Tanks 1 and 2.
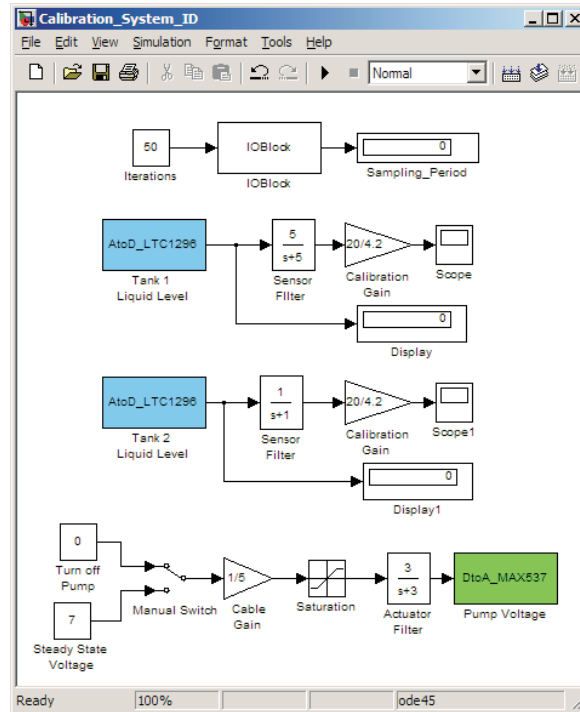

Figure 5: Calibration and System Identification Simulink Block Diagram

6.1. System Identification

In performing experiment 1, as outlined in Section 4, we applied a constant 7 Volt signal to the pump V_{pss}, which produced a steady state liquid level in Tank 1 of $L_{1ss} = 10.75$ cm and a steady state liquid level in Tank 2 of $L_{2ss} = 11.40$ cm. Next, we performed experiment 2 outlined in Section 4 by filling Tank 1 with 16.46 cm of water, i.e., $L_1(t_0) = 16.46$ cm, and obtained the liquid level of Tank 1 as it was discharged. Figure 6 (a) shows the liquid level time history of Tank 1. From Figure 6 (a), the initial time of discharge t_0 is 11.5 sec and the time of full discharge t^* is 26 sec. To compute the system parameter A, we chose $\bar{t} = 16$ sec, which corresponds to a liquid level in Tank 1 of $L_1(\bar{t}) = 10$ cm. Using (4.6) and (4.7), A and B are computed numerically to be 0.3978 and 0.1863, respectively.

Next, we performed experiment 3 outlined in Section 4 by filling Tank 2 with 15.80 cm of water, i.e., $L_2(t_0)$=15.80 cm, and obtained the liquid level of Tank 2 as it was discharged. Figure 6 (b) shows the liquid level time history of Tank 2. From Figure 6 (b), the initial time of discharge t_0 is 59.5 sec and the time of full discharge t^* is 76 sec. To compute the system parameter D, we chose $\hat{t} = 66$ sec, which corresponds to a liquid level in Tank 2 of $L_2(\bar{t}) = 7.8$ cm. Using (4.8) and (4.9), C and D are computed numerically to be 0.4056 and 0.3938, respectively.

Next, we used the liquid level time histories given in Figure 6 to obtain numerous time instances $\bar{t}$ and $\hat{t}$, corresponding to many estimates of the system parameters $A, B, C,$ and D. We then averaged, individually, the estimates of $A, B, C,$ and D and obtained the following: $A = 0.4382$, $B = 0.2052$, $C = 0.4486$, $D = 0.4356$. For comparison, manufacturer specifications of the Tank 1 and 2 cross-sectional areas and orifices areas produce the nominal system parameters $A = 0.5128$, $B = 0.2991$, $C = 0.5128$, and $D = 0.5128$.
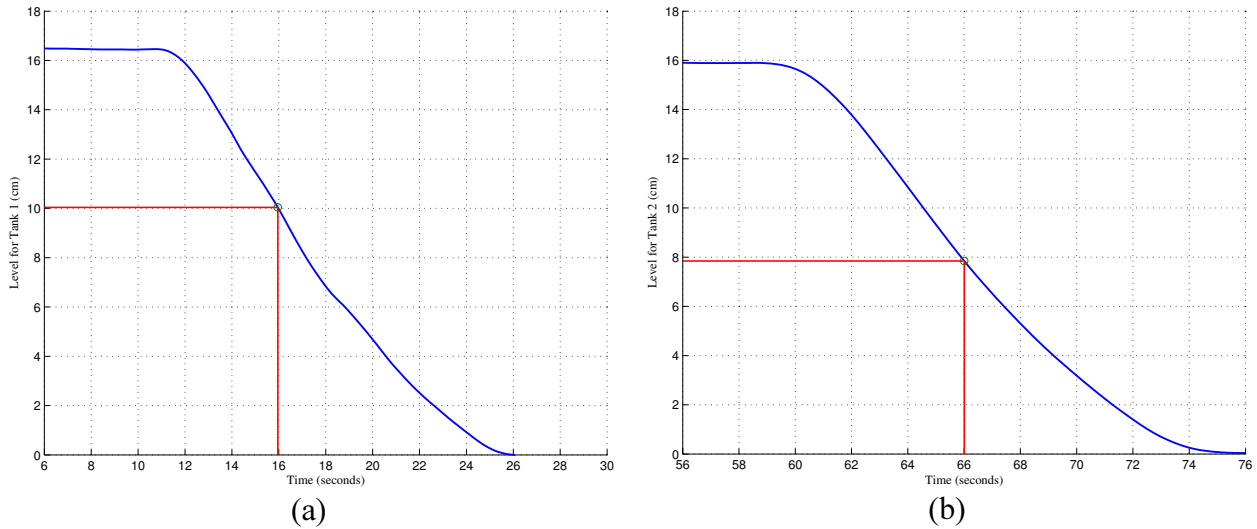

(a)   (b)

Figure 6: (a) Experiment 2—$L_1(t)$ Response and (b) Experiment 3—$L_2(t)$ Response

6.2. PI Liquid Level Control

Next, we implement the PI control architecture of Section 5 to control the liquid level of Tank 2. Referring to Figure 3, two A2D blocks labeled *Tank 1 and 2 Liquid Level*, are used to import the signals $L_1(t)$ and $L_2(t)$. These sensor signals are then used for the PI controller of Tanks 1 and 2, wherein the control signal $V_p(t)$ is sent to a D2A block labeled *Pump Voltage* for output to the pump.

In this experiment, we specify the desired liquid level of Tank 2 to be $L_{2d} = 12$ cm. Next, we design the control gains $K_{Pi}, K_{Ii}, i = 1,2$ using (5.4)–(5.5) given a set of settling time and overshoot performance criterion. The resulting control gains are shown in Table 1.

Table 1: Settling Time and Percent Overshoot Requirements and PI Controller Gains

	T_{s1}	o_1	T_{s2}	o_2	K_{P1}	K_{I1}	K_{P2}	K_{I2}
Case 1	20 sec	1.5%	30 sec	1.5%	1.6315	0.3039	3.0559	0.3288
Case 2	35 sec	1.5%	50 sec	1.5%	0.7963	0.0785	1.4565	0.1184
Case 3	60 sec	1.5%	70 sec	3.5%	0.3322	0.0267	0.7710	0.0641

Figures 7–9 show the time history of $L_1(t)$ and $L_2(t)$ using the control gains given in Cases 1–3 given in Table 1. Note that the controller design for the system is obtained by linearizing the nonlinear model near the predetermined steady state level of Tank 2. Therefore, the response is not guaranteed to satisfy the imposed constraints.
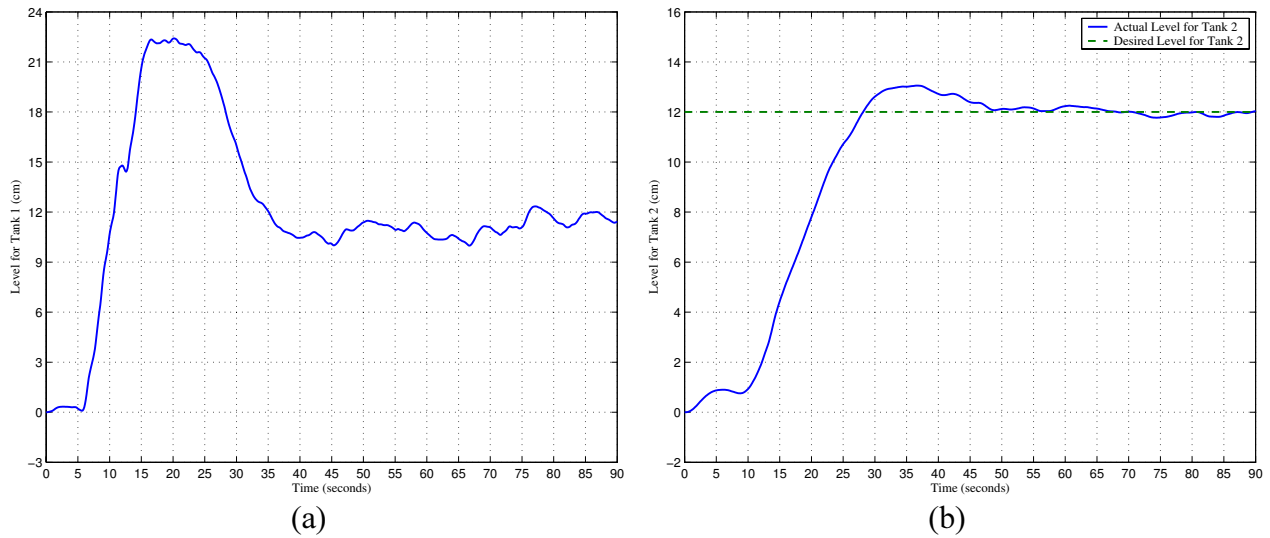

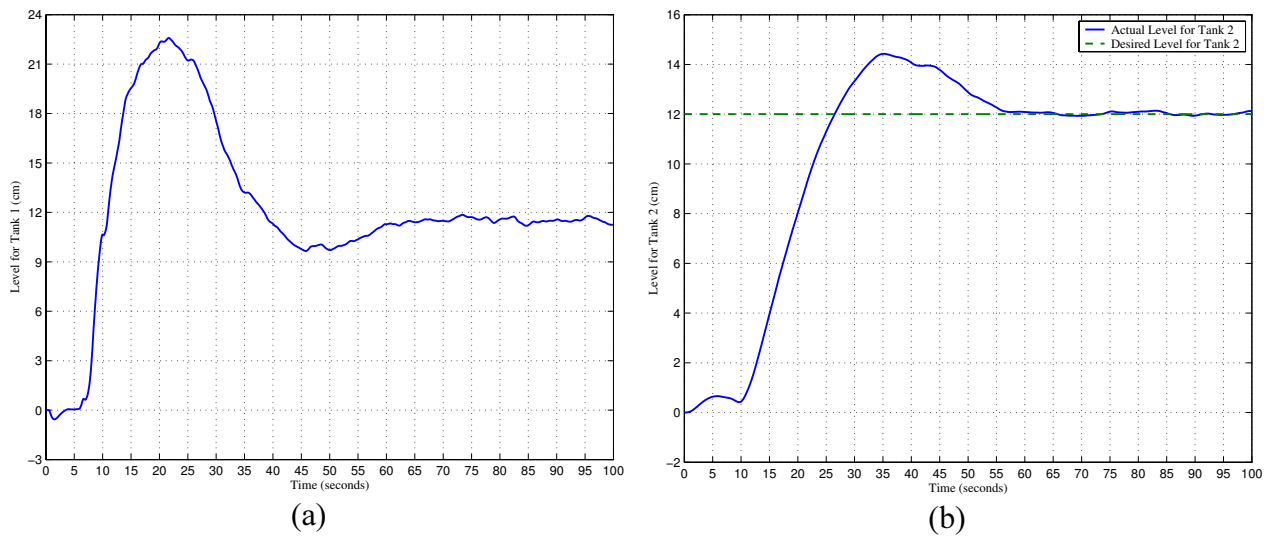Figure 7: Response of (a) $L_1(t)$ and (b) $L_2(t)$ using the PI Controller Gains of Case 1

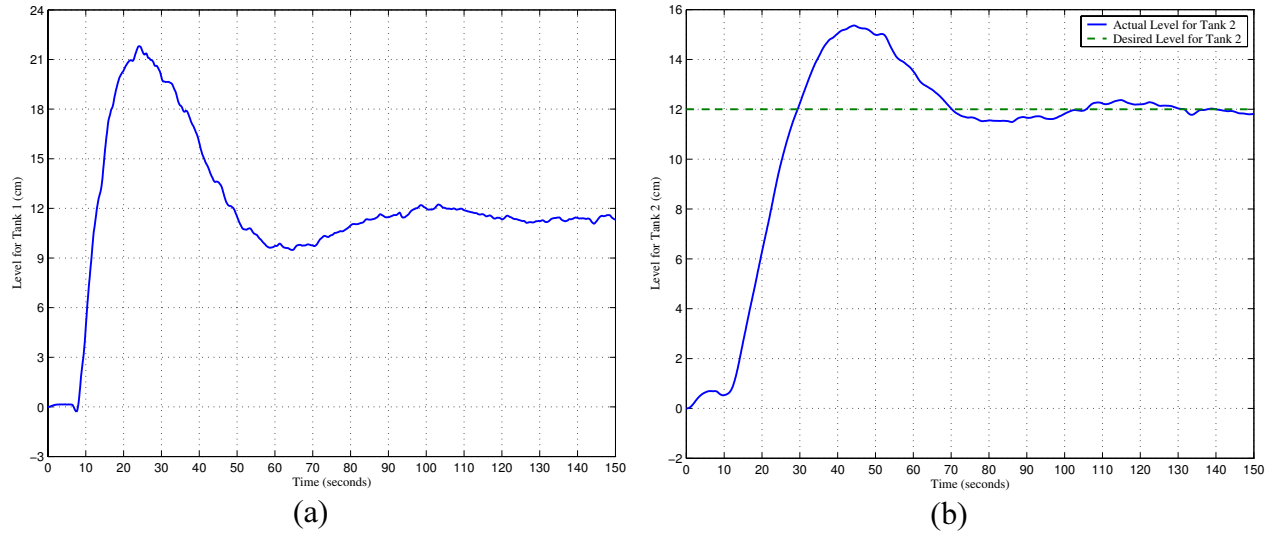Figure 8: Response of (a) $L_1(t)$ and (b) $L_2(t)$ using the PI Controller Gains of Case 2

(a)　　　　　　　　　　　　　　　　　　(b)

Figure 9: Response of (a) $L_1(t)$ and (b) $L_2(t)$ using the PI Controller Gains of Case 3

7. Conclusion

In this paper, we utilized a Matlab and Simulink based data acquisition and control platform[3] to control a two degree-of-freedom, state-coupled, two-tank system. We provided a self contained brief overview of the DAC platform, outlined a comprehensive method to perform system identification, and provided a design of a set-point tracking controller to control the liquid level of the two-tank system. In addition, we experimentally validated the system identification method, which produced estimates of the two-tank system parameters. Finally, we experimentally obtained the response of the set-point tracking controller, which showed good tracking performance using several sets of performance criterion. The paper illustrates that the integration of a low-cost BS2 microcontroller and the Matlab and Simulink based DAC toolbox can be used for data acquisition, experimental system identification, and advanced feedback control.

Acknowledgements

References

1. Online: http://www.mathworks.com/products/simulink/, website of MathWorks Inc., developer and distributor of Matlab.
2. Online: http://www.mathworks.com/products/simulink/, website of MathWorks Inc., developer and distributor of Simulink

3. A. Panda, H. Wong, V. Kapila, and S. Lee "Matlab Data Acquisition and Control Toolbox for Basic Stamp Microcontrollers," available at http://mechatronics.poly.edu/projects/papers/MatLabDACToolbox.pdf.

4. Online: http://www.parallax.com/detail.asp?product_id=BS2-IC, website of Parallax Inc., developer and distributor of the Basic Stamp 2 (BS2-IC) microcontroller (access link for BS2-IC product information).

5. H. Pan, H. Wong, V. Kapila, and M. S. de Queiroz, "Experimental Validation of a Nonlinear Backstepping Liquid Level Controller for a State Coupled Two Tank System," Journal of Control Engineering Practice, Vol. 13, pp. 27–40, 2005.

6. Online: http://www.linear.com/prod/datasheet.html?datasheet=324, website of Linear Technology Inc. developer and distributor of the LTC1296 ADC (access link for product information).

7. Online: http://www.maxim-ic.com/quick_view2.cfm?qv_pk=1125, website of Dallas Semiconductor Inc. developer and distributor of the MAX537 DAC (access link for product information).

8. R. N. Bateson, *Introduction to Control System Technology*, Prentice-Hall, Upper Saddle River, NJ, 1999.

9. Online:http://www.quanser.com/english/html/products/fs_product_challenge.asp?lang_code=english&pcat_code=exp-rot&prod_code=R1-posserv, website of Quanser Consulting Inc. developer and distributor of the DC motor test-bed (access link for product information).