



INSTRUCTOR WORKBOOK

Coupled Tanks Experiment for LabVIEW™ Users

Standardized for ABET* Evaluation Criteria

Developed by:
Jacob Apkarian, Ph.D., Quanser
Hervé Lacheray, M.A.SC., Quanser
Amin Abdossalami, M.A.SC., Quanser

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PREFACE

Preparing laboratory experiments can be time-consuming. Quanser understands time constraints of teaching and research professors. That's why Quanser's control laboratory solutions come with proven practical exercises. The courseware is designed to save you time, give students a solid understanding of various control concepts and provide maximum value for your investment.

Quanser courseware materials are supplied in two formats:

1. Instructor Workbook – provides solutions for the pre-lab assignments and contains typical experimental results from the laboratory procedure. This version is not intended for the students.
2. Student Workbook – contains pre-lab assignments and in-lab procedures for students.

This courseware material is prepared for users of National Instruments **LabVIEW™** software.



The courseware for Coupled Tanks experiment is aligned with the requirements of the Accreditation Board for Engineering and Technology (ABET), one of the most respected organizations specializing in accreditation of educational programs in applied science, computing, science and technology. The Instructor Workbook provides professors with a simple framework and set of templates to measure and document students' achievements of various performance criteria and their ability to:



- Apply knowledge of math, science and engineering
- Design and conduct experiments, and analyze and interpret data
- Communicate effectively
- Use techniques, skills and modern engineering tools necessary for engineering practice

Quanser, Inc. would like to thank Dr. Karl Åstrom from Lund University, Sweden for his immense contribution to the courseware content and Dr. Hakan Gurocak from the Washington State University Vancouver, for rewriting the original manual to include embedded outcomes assessment.

The following material provides an abbreviated example of pre-lab assignments and in-lab procedures for the Coupled Tanks experiment. Please note that the examples are not complete as they are intended to give you a brief overview of the structure and content of the course materials you will receive with the plant.

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1. INTRODUCTION TO QUANSER COUPLED TANKS COURSEWARE SAMPLE

Quanser courseware provides step-by-step pedagogy for a wide range of control challenges. Starting with the basic principles, students can progress to more advanced applications and cultivate a deep understanding of control theories. Quanser Coupled Tanks courseware covers topics, such as:

- How to mathematically model the Coupled-Tank plant from first principles in order to obtain the two open-loop transfer functions characterizing the system, in the Laplace domain
- How to linearize the obtained non-linear equation of motion about the quiescent point of operation
- How to design, through pole placement, a Proportional-plus-Integral-plus-Feedforward-based controller for the Coupled Tanks system in order for it to meet the required design specifications for each configuration
- How to implement each configuration controller(s) and evaluate its/their actual performance

Every laboratory chapter in the Instructor Workbook is organized into four sections:

- **Background section** provides all the necessary theoretical background for the experiments. Students should read this section first to prepare for the Pre-Lab questions and for the actual lab experiments.
- **Pre-Lab Questions section** is not meant to be a comprehensive list of questions to examine understanding of the entire background material. Rather, it provides targeted questions for preliminary calculations that need to be done prior to the lab experiments. All or some of the questions in the Pre-Lab section can be assigned to the students as homework.
- **Lab Experiments section** provides step-by-step instructions to conduct the lab experiments and to record the collected data.
- **System Requirements section** describes all the details of how to configure the hardware and software to conduct the experiments. It is assumed that the hardware and software configuration have been completed by the instructor or the teaching assistant prior to the lab sessions. However, if the instructor chooses to, the students can also configure the systems by following the instructions given in this section.

Assessment of ABET outcomes is incorporated into the Instructor Workbook – look for indicators such as A-1, A-2. These indicators correspond to specific performance criteria for an outcome. **Appendix A** of the Instructor Workbook includes:

- details of the targeted ABET outcomes,
- list of performance criteria for each outcome,
- scoring rubrics and instructions on how to use them in assessment.

The outcomes targeted by the Pre-Lab questions can be assessed using the student work. The outcomes targeted by the lab experiments can be assessed from the lab reports submitted by the students. These reports should follow the specific template for content given at the end of each laboratory chapter. This will provide a basis to assess the outcomes easily.

2. INSTRUCTOR WORKBOOK TABLE OF CONTENTS

The full Table of Contents of the Quanser Coupled Tanks Instructor Workbook is shown here:

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 - 2.1. BACKGROUND
 - 2.1.1. CONFIGURATION #1 SYSTEM SCHEMATICS
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 - 2.1.5. CONFIGURATION #2 NONLINEAR EQUATION OF MOTION (EOM)
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 - 4.1. BACKGROUND
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 - 4.1.2. TANK 2 LEVEL CONTROLLER DESIGN: POLE PLACEMENT
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- 7.1. MODELING PRE-LAB QUESTIONS
- 7.2. TANK 1 LEVEL CONTROL PRE-LAB QUESTIONS
- 7.3. TANK 1 LEVEL CONTROL LAB REPORT
- 7.4. TANK 2 LEVEL CONTROL PRE-LAB QUESTIONS
- 7.5. TANK 2 LEVEL CONTROL LAB REPORT

APPENDIX A – NOMENCLATURE

APPENDIX B - INSTRUCTOR'S GUIDE

- B.1 PRE-LAB QUESTIONS AND LAB EXPERIMENTS
 - B.1.1. HOW TO USE THE PRE-LAB QUESTIONS
 - B.1.2. HOW TO USE THE LABORATORY EXPERIMENTS
- B.2 ASSESSMENT FOR ABET ACCREDITATION
 - B.2.1. ASSESSMENT IN YOUR COURSE
 - B.2.2. HOW TO SCORE THE PRE-LAB QUESTIONS
 - B.2.3. HOW TO SCORE THE LAB REPORT
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 - B.2.6. COURSE SCORES FOR OUTCOMES B, K AND G
 - B.2.7. ASSESSMENT WORKBOOK
- B.3 RUBRICS

REFERENCES

3. BACKGROUND SECTION - SAMPLE

Configuration #1 System Schematics

A schematic of the Coupled-Tank plant is represented in Figure 2.1, below. The Coupled-Tank system's nomenclature is provided in Appendix A. As illustrated in Figure 2.1, the positive direction of vertical level displacement is upwards, with the origin at the bottom of each tank (i.e. corresponding to an empty tank), as represented in Figure 3.2.

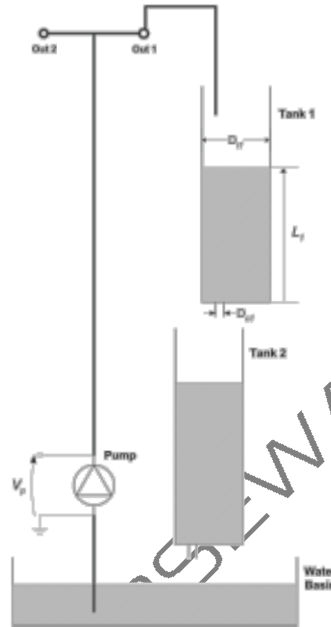


Figure 2.1: Schematic of Coupled Tanks in Configuration #1.

Configuration #1 Nonlinear Equation of Motion (EOM)

In order to derive the mathematical model of your Coupled-Tank system in configuration #1, it is reminded that the pump feeds into Tank 1 and that tank 2 is not considered at all. Therefore, the input to the process is the voltage to the pump V_p and its output is the water level in tank 1, L_1 , (i.e. top tank).

The purpose of the present modeling session is to provide you with the system's open-loop transfer function, $G1(s)$, which in turn will be used to design an appropriate level controller. The obtained Equation of Motion, EOM, should be a function of the system's input and output, as previously defined.

Therefore, you should express the resulting EOM under the following format:

$$\frac{\partial L_1}{\partial t} = f(L_1, V_p)$$

where f denotes a function. In deriving the Tank 1 EOM the mass balance principle can be applied to the water level in tank 1, i.e.,

$$A_{t1} \frac{\partial L_1}{\partial t} = F_{i1} - F_{o1} \quad (2.1)$$

where A_{t1} is the area of Tank 1. F_{i1} and F_{o1} are the inflow rate and outflow rate, respectively. The volumetric inflow rate to tank 1 is assumed to be directly proportional to the applied pump voltage, such that:

$$F_{i1} = K_p V_p$$

Applying Bernoulli's equation for small orifices, the outflow velocity from tank 1, v_{o1} , can be expressed by the following relationship:

$$v_{o1} = \sqrt{2gL_1}$$

4. PRE-LAB QUESTIONS SECTION - SAMPLE

Modeling

Answer the following questions:

1. **A-1, A-2, A-3** Using the notations and conventions described in Figure 2 derive the Equation Of Motion (EOM) characterizing the dynamics of tank 1. Is the tank 1 system's EOM linear?

Hint: The outflow rate from tank 1, F_{o1} , can be expressed by:

$$F_{o1} = A_{o1}v_{o1p} \quad (2.12)$$

Answer 3.1

Outcome

Solution

A-1

As a remark, the cross-section area of tank 1 outlet hole can be calculated by:

$$A_{o1} = \frac{1}{4}\pi D_{o1}^2 \quad (\text{Ans. 2.1})$$

Using Equation Ans.2.1, the outflow rate from tank 1 given in Equation 2.12 becomes:

$$F_{o1} = A_{o1}\sqrt{2gL_1} \quad (\text{Ans.2.2})$$

A-2

Moreover, using the mass balance principle for tank 1, we obtained a first-order differential equation for L_1 in Equation 2.1. Substituting in Equation 2.1 F_{i1} and F_{o1} with their expressions given in Equation Ans.2.1 and Equation Ans.2.2, respectively, and rearranging results in the following equation of motion for the tank 1 system:

$$\frac{\partial L_1}{\partial t} = \frac{K_p V_p - A_{o1}\sqrt{2}\sqrt{gL_1}}{A_{t1}} \quad (\text{Ans.2.3})$$

A-2

The EOM of tank 1 in Equation Ans.2.3 is nonlinear.



5. LAB EXPERIMENTS SECTION - SAMPLE

Tank 2 Level Control Simulation

Experimental Setup

The *Coupled Tanks - Tank2 Level Control simulation VI* shown in Figure 4.2 is used to perform tank 2 level control simulation exercises in this laboratory.

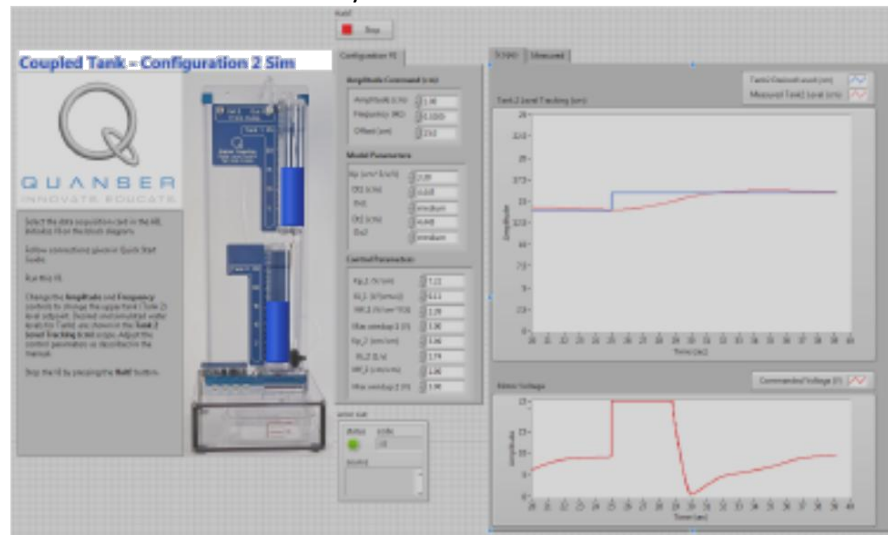


Figure 4.2: VI used to run PI-FF control Simulation on Coupled Tanks system in configuration #2.

IMPORTANT: Before you can conduct these experiments, you need to make sure that the lab files are configured. If they have not been configured already, then go to Section 5 to configure the lab files first.

Follow this procedure:

1. In *Coupled Tanks.lvproj*, open *Coupled Tanks- Tank2 Level Control Simulation.vi*. The model implements the system's simulation Proportional-plus-Integral (PI) closed-loop with feedforward action, as studied in Section 4.1.2. As mentioned in the pre-lab assignments, the tank 2 water level control loop is based on tank 1 level controller, as developed and tuned in the previous sections. The level controller diagram for the Coupled Tank in configuration #2 also interfaces directly with your Coupled Tank hardware. To familiarize yourself with the diagram, it is suggested that you open the model subsystems to get a better idea of their composing blocks as well as take note of the I/O connections.
2. To generate a square wave that goes between 14 and 16 cm for the tank 2 level reference, go to the *Amplitude Command (cm)* section and set the controls to the following:
 - Amplitude = 1 cm
 - Frequency = 0.02 Hz
 - Offset = 15 cm

The total level setpoint for tank 2 should result to be a square wave of ± 1 cm around the desired equilibrium level L_{20}

3. Enter the proportional, integral, and feedforward control gains found in Section 4.2 in the $k_p 2$, $k_i 2$, and $k_{ff} 2$ controls in the *Control Parameters* section on the front panel. Keep in the the PI-plus-feedforward

controller gains for tank 1 of the Coupled-Tank system in configuration #1, as previously implemented. Those are $kp\ 1$, $ki\ 1$, and $kff\ 1$ controls in the *Control Parameters* section on the front panel. Have your lab assistant check your values.

4. Run the VI.
5. The VI should start the Coupled Tanks simulation filling tank1 and tank 2 up to their operating levels $L10$ and $L20$, respectively. Then after a 35-second settling delay (in order to stabilize the system at its operating point), the water level in tank 2 should start tracking the desired $\pm 1\text{cm}$ square wave setpoint around the desired operating level $L20$. The corresponding commanded pump voltage, which is proportional to the control effort spent, can also be monitored and plotted on-line.
6. **B-5, K-2** Attach a plot showing the *Implemented Tank 2 Control* response and the input voltage.

Answer 4.5

Outcome Solution

B-5 If the procedure was followed properly, Tank 2 level control simulation file should have been run. The response similar to Figure 4.3 should have been obtained.

K-2 The closed-loop Tank 2 level response is shown in Figure 4.3.



7. **K-1, B-9** Assess the actual performance of the level response and compare it to the design requirements. Measure your response actual percent overshoot and settling time. Are the design specifications satisfied? Explain. If your level response does not meet the desired design specifications, review your PI-plus-Feedforward gain calculations and/or alter the closed-loop pole locations until they do. If you are still unable to achieve the required performance level, ask your lab instructor for advice. Does the response satisfy the specifications given in Section 2.1.4?

Hint: Use the graph cursors in the *Measure* tab to take measurements.

Answer 4.6

Outcome Solution

K-1 The settling time in the response shown in Figure 4.5 is
 $t_{s2} = 0\text{ cm}$

The peak time and percentage overshoot of the response are:

$$t_{p2} = 40 - 25 = 15\text{ sec}$$

and

$$PO_2 = 100 \times \frac{16.3 - 16}{16} = 1.8\%$$

B-9 Both the peak time and percent overshoot measured satisfy the specifications given in Section 2.1.4.



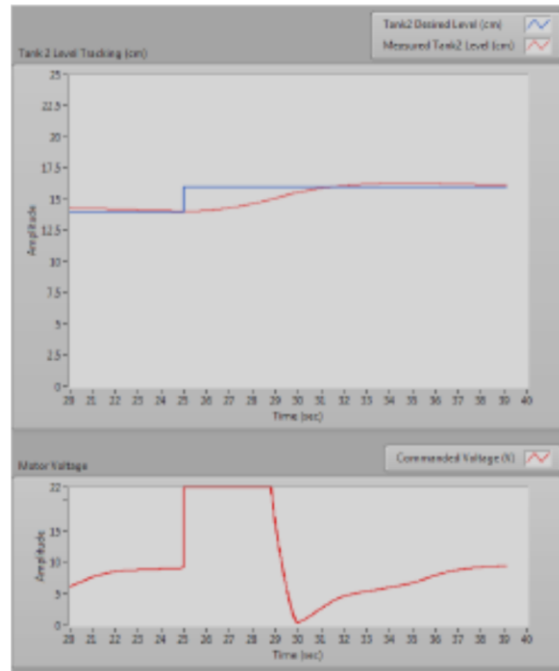


Figure 4.3: Tank 2 level closed-loop control response.

Process control plants for teaching and research



These plants are ideal for intermediate level teaching. They are also suitable for research relating to traditional or modern control applications of process control. For more information please contact info@quanser.com

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INFO@QUANSER.COM

+1-905-940-3575

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