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# INSTRUCTOR WORKBOOK

## Coupled Tanks Experiment for MATLAB®/Simulink® Users

### Standardized for ABET* Evaluation Criteria

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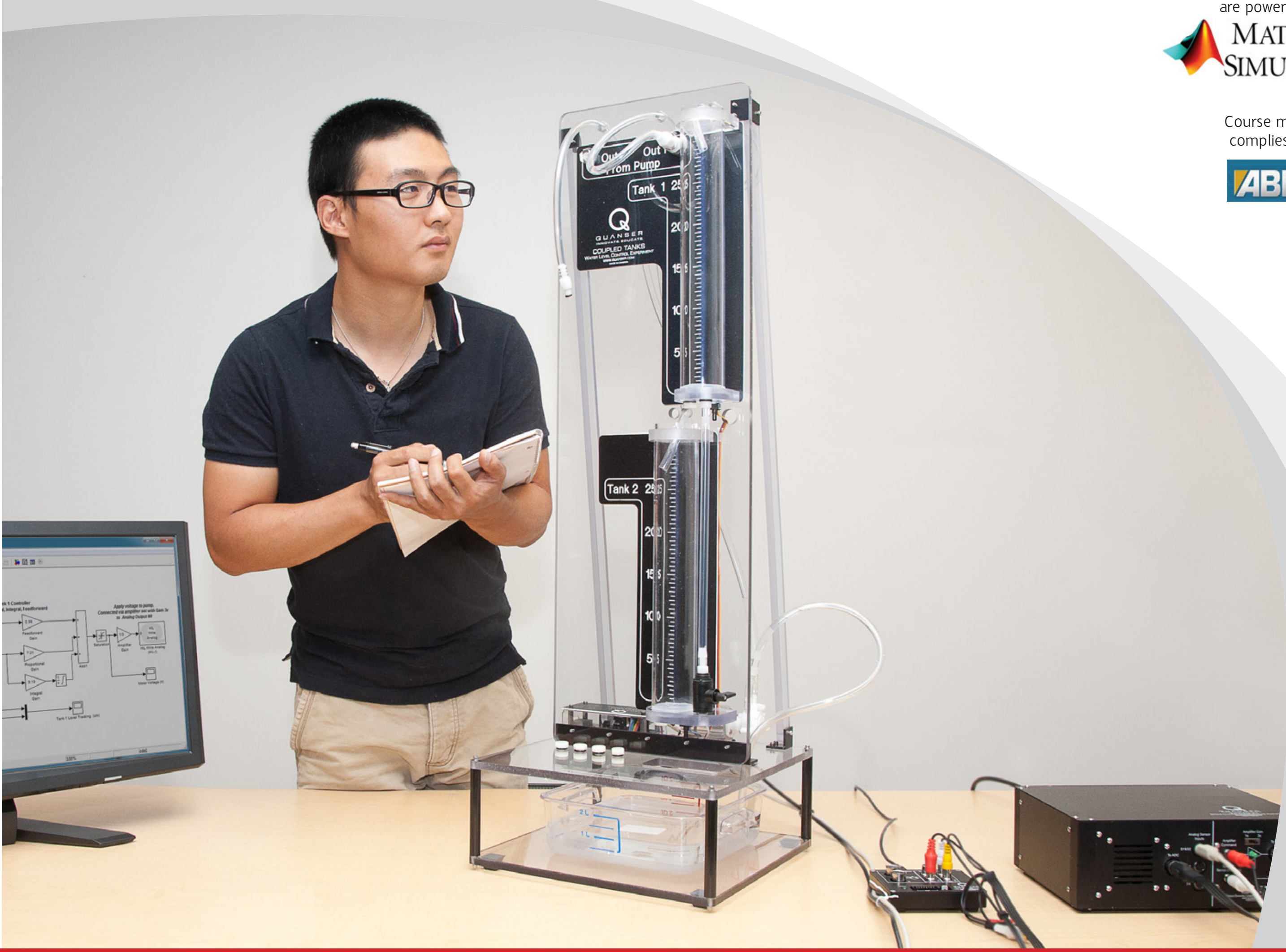

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# CONTENTS

# 1 INTRODUCTION

The Coupled Tanks plant is a "Two-Tank" module consisting of a pump with a water basin and two tanks. The two tanks are mounted on the front plate such that flow from the first (i.e. upper) tank can flow, through an outlet orifice located at the bottom of the tank, into the second (i.e. lower) tank. Flow from the second tank flows into the main water reservoir. The pump thrusts water vertically to two quick-connect orifices "Out1" and "Out2". The two system variables are directly measured on the Coupled-Tank rig by pressure sensors and available for feedback. They are namely the water levels in tanks 1 and 2. A more detailed description is provided in [5]. To name a few, industrial applications of such Coupled-Tank configurations can be found in the processing system of petro-chemical, paper making, and/or water treatment plants.

During the course of this experiment, you will become familiar with the design and pole placement tuning of Proportional-plus-Integral-plus-Feedforward-based water level controllers. In the present laboratory, the Coupled-Tank system is used in two different configurations, namely configuration #1 and configuration #2, as described in [5]. In configuration #1, the objective is to control the water level in the top tank, i.e., tank #1, using the outflow from the pump. In configuration #2, the challenge is to control the water level in the bottom tank, i.e. tanks #2, from the water flow coming out of the top tank. Configuration #2 is an example of state coupled system.

**Topics Covered**

- 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-Tank 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.

**Prerequisites**

In order to successfully carry out this laboratory, the user should be familiar with the following:

1. See the system requirements in Section 5 for the required hardware and software.
2. Transfer function fundamentals, e.g., obtaining a transfer function from a differential equation.
3. Familiar with designing PID controllers.
4. Basics of Simulink®.
5. Basics of QUARC®.

# 2 MODELING

## 2.1 Background

### 2.1.1 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.

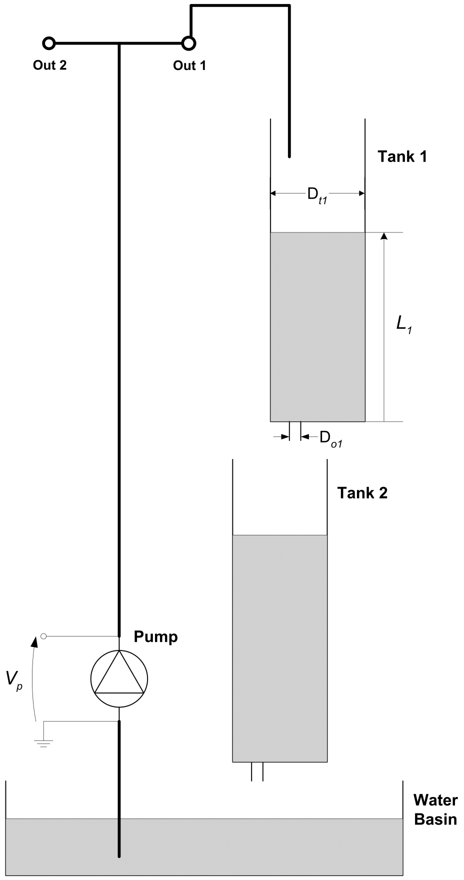


Figure 2.1: Schematic of Coupled Tank in Configuration #1.

### 2.1.2 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 modelling 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.,

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

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:

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

### 2.1.3 Configuration # 1 EOM Linearization and Transfer Function

In order to design and implement a linear level controller for the tank 1 system, the open-loop Laplace transfer function should be derived. However by definition, such a transfer function can only represent the system's dynamics from a linear differential equation. Therefore, the nonlinear EOM of tank 1 should be linearized around a quiescent point of operation. By definition, static equilibrium at a nominal operating point $(V_{p0}, L_{10})$ is characterized by the Tank 1 level being at a constant position $L_{10}$ due to a constant water flow generated by constant pump voltage $V_{p0}$.

In the case of the water level in tank 1, the operating range corresponds to small departure heights, $L_{11}$, and small departure voltages, $V_{p1}$, from the desired equilibrium point $(V_{p0}, L_{10})$. Therefore, $L_1$ and $V_p$ can be expressed as the sum of two quantities, as shown below:

$$L_1 = L_{10} + L_{11}, \qquad V_p = V_{p0} + V_{p1} \tag{2.2}$$

The obtained linearized EOM should be a function of the system's small deviations about its equilibrium point $(V_{p0}, L_{10})$. Therefore, one should express the resulting linear EOM under the following format:

$$\frac{\partial}{\partial t} L_{11} = f(L_{11}, V_{p1}) \tag{2.3}$$

where $f$ denotes a function.

**Example: Linearizing a Two-Variable Function**
Here is an example of how to linearize a two-variable nonlinear function called $f(z)$. Variable $z$ is defined

$$z^{\top} = [z_1 \; z_2]$$

and $f(z)$ is to be linearized about the operating point

$$z_0{}^{\top} = [a \; b]$$

The linearized function is

$$f_z = f(z_0) + \left(\frac{\partial f(z)}{\partial z_1}\right)\Bigg|_{z=z_0}(z_1 - a) + \left(\frac{\partial f(z)}{\partial z_2}\right)\Bigg|_{z=z_0}(z_2 - b)$$

For a function, $f$, of two variables, $L_1$ and $V_p$, a first-order approximation for small variations at a point $(L_1, V_p) = (L_{10}, V_{p0})$ is given by the following Taylor's series approximation:

$$\frac{\partial^2}{\partial L_1 \partial V_p} f\left(L_1, V_p\right) \cong f\left(L_{10}, V_{p0}\right) + \left(\frac{\partial}{\partial L_1} f\left(L_{10}, V_{p0}\right)\right) + \left(L_1 - L_{10}\right)\left(\frac{\partial}{\partial V_p} f\left(L_{10}, V_{p0}\right)\right)\left(V_p - V_{p0}\right) \tag{2.4}$$

**Transfer Function**
From the linear equation of motion, the system's open-loop transfer function in the Laplace domain can be defined by the following relationship:

$$G_1(s) = \frac{L_{11}(s)}{V_{p1}(s)} \tag{2.5}$$

The desired open-loop transfer function for the Coupled-Tank's tank 1 system is the following:

$$G_1(s) = \frac{K_{dc1}}{\tau_1 s + 1} \tag{2.6}$$

where $K_{dc_1}$ is the open-loop transfer function DC gain, and $\tau_1$ is the time constant.

As a remark, it is obvious that linearized models, such as the Coupled-Tank tank 1's voltage-to-level transfer function, are only approximate models. Therefore, they should be treated as such and used with appropriate caution, that is to say within the valid operating range and/or conditions. However for the scope of this lab, Equation 2.5 is assumed valid over the pump voltage and tank 1 water level entire operating range, $V_{p\_peak}$ and $L_{1\_max}$, respectively.

### 2.1.4 Configuration #2 System Schematics

A schematic of the Coupled-Tank plant is represented in Figure 2.2, below. The Coupled-Tank system's nomenclature is provided in Appendix A. As illustrated in Figure 2.2, 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 2.2.

### 2.1.5 Configuration #2, Nonlinear Equation of Motion (EOM)

This section explains the mathematical model of your Coupled-Tank system in configuration #2, as described in Reference [1]. It is reminded that in configuration #2, the pump feeds into tank 1, which in turn feeds into tank 2. As far as tank 1 is concerned, the same equations as the ones explained in Section 2.1.2 and Section 2.1.3 will apply. However, the water level Equation Of Motion (EOM) in tank 2 still needs to be derived. The input to the tank 2 process is the water level, $L_1$, in tank 1 (generating the outflow feeding tank 2) and its output variable is the water level, $L_2$, in tank 2 (i.e. bottom tank). The purpose of the present modelling session is to guide you with the system's open-loop transfer function, $G_2(s)$, which in turn will be used to design an appropriate level controller. The obtained 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:

$$\frac{\partial L_2}{\partial t} = f(L_2, L_1)$$

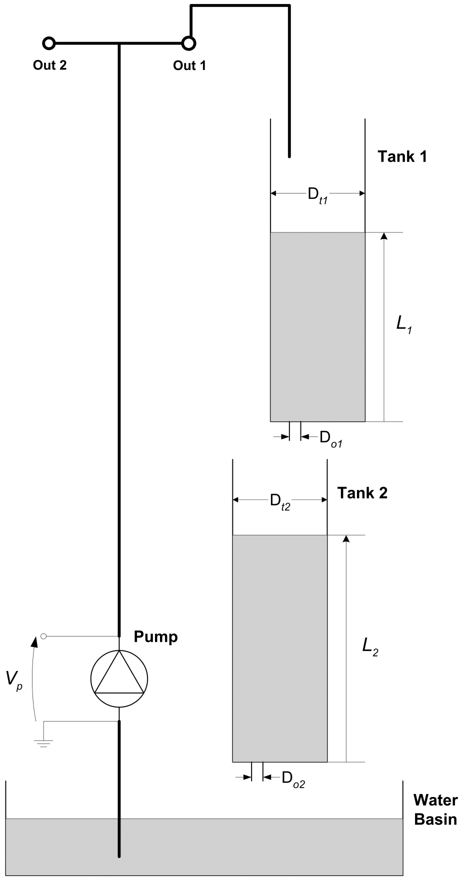


Figure 2.2: Schematic of Coupled Tank in configuration #1.

where $f$ denotes a function.

In deriving the tank #2 EOM the mass balance principle can be applied to the water level in tank 2 as follows

$$A_{t2}\frac{\partial L_2}{\partial t} = F_{i2} - F_{o2}$$

where $A_{t2}$ is the area of tank 2. $F_{i2}$ and $F_{o2}$ are the inflow rate and outflow rate, respectively.

The volumetric inflow rate to tank 2 is equal to the volumetric outflow rate from tank 1, that is to say:

$$F_{i2} = F_{o1}$$

Applying Bernoulli's equation for small orifices, the outflow velocity from tank 2, $v_{o2}$, can be expressed by the following relationship:

$$v_{o2} = \sqrt{2gL_2}$$

### 2.1.6 Configuration #2 EOM Linearization and Transfer Function

In order to design and implement a linear level controller for the tank 2 system, the Laplace open-loop transfer function should be derived. However by definition, such a transfer function can only represent the system's dynamics from a linear differential equation. Therefore, the nonlinear EOM of tank 2 should be linearized around a quiescent point of operation.

In the case of the water level in tank 2, the operating range corresponds to small departure heights, $L_{11}$ and $L_{21}$, from the desired equilibrium point $(L_{10}, L_{20})$. Therefore, $L_2$ and $L_1$ can be expressed as the sum of two quantities, as shown below:

$$L_2 = L_{20} + L_{21}, \qquad L_1 = L_{10} + L_{11} \tag{2.7}$$

The obtained linearized EOM should be a function of the system's small deviations about its equilibrium point $(L_{20}, L_{10})$. Therefore, you should express the resulting linear EOM under the following format:

$$\frac{\partial}{\partial t} L_{21} = f(L_{11}, L_{21}) \tag{2.8}$$

where $f$ denotes a function.

For a function, $f$, of two variables, $L_1$ and $L_2$, a first-order approximation for small variations at a point $(L_1, L_2) = (L_{10}, L_{20})$ is given by the following Taylor's series approximation:

$$\frac{\partial^2}{\partial L_1 \partial L_2} f\left(L_1, L_2\right) \cong f\left(L_{10}, L_{20}\right) + \left(\frac{\partial}{\partial L_1} f\left(L_{10}, L_{20}\right)\right) + \left(L_1 - L_{10}\right)\left(\frac{\partial}{\partial L_2} f\left(L_{10}, L_{20}\right)\right)\left(L_2 - L_{20}\right) \tag{2.9}$$

**Transfer Function**

From the linear equation of motion, the system's open-loop transfer function in the Laplace domain can be defined by the following relationship:

$$G_2(s) = \frac{L_{21}(s)}{L_{11}(s)} \tag{2.10}$$

the desired open-loop transfer function for the Coupled-Tank's tank 2 system, such that:

$$G_2(s) = \frac{K_{dc2}}{\tau_2 s + 1} \tag{2.11}$$

where $K_{dc_2}$ is the open-loop transfer function DC gain, and $\tau_2$ is the time constant.

As a remark, it is obvious that linearized models, such as the Coupled-Tank's tank 2 level-to-level transfer function, are only approximate models. Therefore, they should be treated as such and used with appropriate caution, that is to say within the valid operating range and/or conditions. However for the scope of this lab, Equation 2.10 is assumed valid over tank 1 and tank 2 water level entire range of motion, $L_{1\_max}$ and $L_{2\_max}$, respectively.

## 2.2 Pre-Lab Questions

Answer the following questions:

1. 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:

   $$F_{o1} = A_{o1} v_{o1} \tag{2.12}$$

2. The nominal pump voltage $V_{p0}$ for the pump-tank 1 pair can be determined at the system's static equilibrium. By definition, static equilibrium at a nominal operating point $(V_{p0}, L_{10})$ is characterized by the water in tank 1 being at a constant position level $L_{10}$ due to the constant inflow rate generated by $V_{p0}$. Express the static equilibrium voltage $V_{p0}$ as a function of the system's desired equilibrium level $L_{10}$ and the pump flow constant $K_p$. Using the system's specifications given in the Coupled Tanks User Manual ([5]) and the desired design requirements in Section 3.1.1, evaluate $V_{p0}$ parametrically.

3. Linearize tank 1 water level's EOM found in Question #1 about the quiescent operating point $(V_{p0}, L_{10})$.

4. Determine from the previously obtained linear equation of motion, the system's open-loop transfer function in the Laplace domain as defined in Equation 2.5 and Equation 2.6. Express the open-loop transfer function DC gain, $K_{dc_1}$, and time constant, $\tau_1$, as functions of $L_{10}$ and the system parameters. What is the order and type of the system? Is it stable? Evaluate $K_{dc_1}$ and $\tau_1$ according to system's specifications given in the Coupled Tanks User Manual ([5]) and the desired design requirements in Section 3.1.1.

5. Using the notations and conventions described in Figure 2.2, derive the Equation Of Motion (EOM) characterizing the dynamics of tank 2. Is the tank 2 system's EOM linear?

   **Hint:** The outflow rate from tank 2, $F_{o2}$, can be expressed by:

   $$F_{o2} = A_{o2} v_{o2} \tag{2.13}$$

6. The nominal water level $L_{10}$ for the tank1-tank2 pair can be determined at the system's static equilibrium. By definition, static equilibrium at a nominal operating point $(L_{10}, L_{20})$ is characterized by the water in tank 2 being at a constant position level $L_{20}$ due to the constant inflow rate generated from the top tank by $L_{10}$. Express the static equilibrium level $L_{10}$ as a function of the system's desired equilibrium level $L_{20}$ and the system's parameters. Using the system's specifications given in the Coupled Tanks User Manual ([5]) and the desired design requirements in Section 4.1.1, evaluate $L_{10}$.

7. Linearize tank 2 water level's EOM found in Question #5 about the quiescent operating point $(L_{10}, L_{20})$.

8. Determine from the previously obtained linear equation of motion, the system's open-loop transfer function in the Laplace domain, as defined in Equation 2.10 and Equation 2.11. Express the open-loop transfer function DC gain, $K_{dc_2}$, and time constant, $\tau_2$, as functions of $L_{10}$, $L_{20}$, and the system parameters. What is the order and type of the system? Is it stable? Evaluate $K_{dc_2}$ and $\tau_2$ according to system's specifications given in the Coupled Tanks User Manual ([5]) and the desired design requirements in Section 4.1.1.

# 3 TANK 1 LEVEL CONTROL

## 3.1 Background

### 3.1.1 Specifications

In configuration #1, a control is designed to regulate the water level (or height) of tank #1 using the pump voltage. The control is based on a Proportional-Integral-Feedforward scheme (PI-FF). Given a $\pm 1$ cm square wave level setpoint (about the operating point), the level in tank 1 should satisfy the following design performance requirements:

1. Operating level in tank 1 at 15 cm: $L_{10} = 15$ cm.
2. Percent overshoot less than 10%: $PO_1 \leq 11$ %.
3. 2% settling time less than 5 seconds: $t_{s\_1} \leq 5.0$ s.
4. No steady-state error: $e_{ss} = 0$ cm.

### 3.1.2 Tank 1 Level Controller Design: Pole Placement

For zero steady-state error, tank 1 water level is controlled by means of a Proportional-plus-Integral (PI) closed-loop scheme with the addition of a feedforward action, as illustrated in Figure 3.1, below, the voltage feedforward action is characterized by:

$$V_{p\_ff} = K_{ff\_1}\sqrt{L_{r\_1}} \tag{3.1}$$

and

$$V_p = V_{p1} + V_{p\_ff} \tag{3.2}$$

As it can be seen in Figure 3.1, the feedforward action is necessary since the PI control system is designed to compensate for small variations (a.k.a. disturbances) from the linearized operating point $(V_{p0}, L_{10})$. In other words, while the feedforward action compensates for the water withdrawal (due to gravity) through tank 1 bottom outlet orifice, the PI controller compensates for dynamic disturbances.

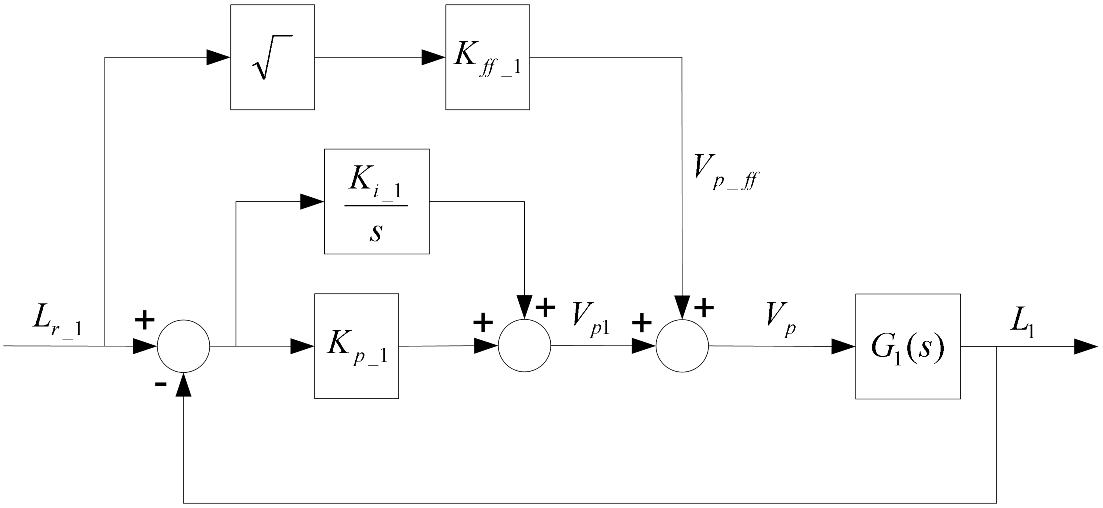


Figure 3.1: Tank 1 Water Level PI-plus-Feedforward Control Loop.

The open-loop transfer function $G_1(s)$ takes into account the dynamics of the tank 1 water level loop, as characterized by Equation 2.5. However, due to the presence of the feedforward loop, $G_1(s)$ can also be written as follows:

$$G_1(s) = \frac{L_1(s)}{V_{p1}(s)} \tag{3.3}$$

### 3.1.3 Second-Order Response

The block diagram shown in Figure 3.2 is a general unity feedback system with compensator, i.e., controller $C(s)$ and a transfer function representing the plant, $P(s)$. The measured output, $Y(s)$, is supposed to track the reference signal $R(s)$ and the tracking has to match to certain desired specifications.

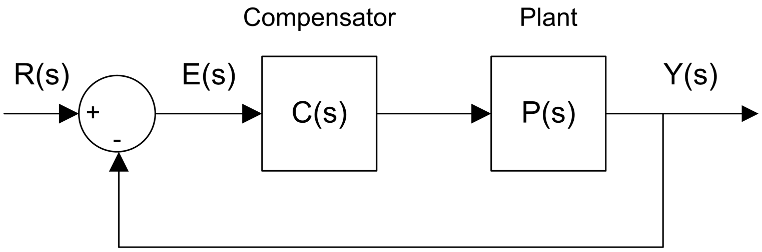


Figure 3.2: Unity feedback system.

The output of this system can be written as:

$$Y(s) = C(s)\,P(s)\,\left(R(s) - Y(s)\right)$$

By solving for $Y(s)$, we can find the closed-loop transfer function:

$$\frac{Y(s)}{R(s)} = \frac{C(s)\,P(s)}{1 + C(s)\,P(s)}$$

The input-output relation in the time-domain for a proportional-integral (PI) controller is

$$u = K_p(r - y) + \frac{K_i(r - y)}{s} \tag{3.4}$$

where $K_p$ is the proportional gain and $K_i$ is the integral gain.

In fact, when a first order system is placed in series with PI compensator in the feedback loop as in Figure 3.2, the resulting closed-loop transfer function can be expressed as:

$$\frac{Y(s)}{R(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\,\omega_n\,s + \omega_n^2} \tag{3.5}$$

where $\omega_n$ is the natural frequency and $\zeta$ is the damping ratio. This is called the *standard second-order* transfer function. Its response properties depend on the values of $\omega_n$ and $\zeta$.

**Peak Time and Overshoot**

Consider a second-order system as shown in Equation 3.5 subjected to a step input given by

$$R(s) = \frac{R_0}{s} \tag{3.6}$$

with a step amplitude of $R_0 = 1.5$. The system response to this input is shown in Figure 3.3, where the red trace is the response (output), $y(t)$, and the blue trace is the step input $r(t)$.

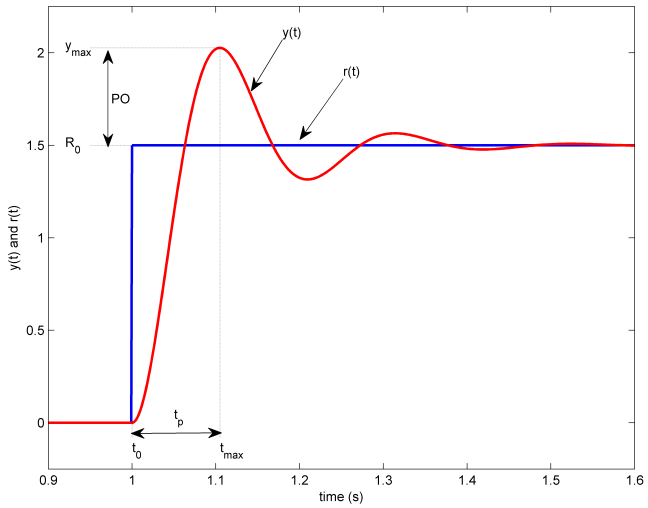


Figure 3.3: Standard second-order step response.

The maximum value of the response is denoted by the variable $y_{max}$ and it occurs at a time $t_{max}$. For a response similar to Figure 3.3, the percent overshoot is found using

$$PO = \frac{100\,(y_{max} - R_0)}{R_0} \tag{3.7}$$

From the initial step time, $t_0$, the time it takes for the response to reach its maximum value is

$$t_p = t_{max} - t_0 \tag{3.8}$$

This is called the *peak time* of the system.

In a second-order system, the amount of overshoot depends solely on the damping ratio parameter and it can be calculated using the equation

$$PO = 100\,e^{\left(-\frac{\pi\,\zeta}{\sqrt{1-\zeta^2}}\right)} \tag{3.9}$$

The peak time depends on both the damping ratio and natural frequency of the system and it can be derived as

$$t_p = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}} \tag{3.10}$$

Tank 1 level response 2% Settling Time can be expressed as follows:

$$t_s = \frac{4}{\zeta\omega} \tag{3.11}$$

Generally speaking, the damping ratio affects the shape of the response while the natural frequency affects the speed of the response.

## 3.2 Pre-Lab Questions

1. Analyze tank 1 water level closed-loop system at the static equilibrium point $(V_{p0}, L_{10})$ and determine and evaluate the voltage feedforward gain, $K_{ff\_1}$, as defined by Equation 3.1.

2. Using tank 1 voltage-to-level transfer function $G_1(s)$ determined in Section 2.2 and the control scheme block diagram illustrated in Figure 3.1, derive the normalized characteristic equation of the water level closed-loop system.

   **Hint#1:** The feedforward gain $K_{ff\_1}$ does not influence the system characteristic equation. Therefore, the feedforward action can be neglected for the purpose of determining the denominator of the closed-loop transfer function. Block diagram reduction can be carried out.

   **Hint#2:** The system's normalized characteristic equation should be a function of the PI level controller gains, $K_{p\_1}$, and $K_{i\_1}$, and system's parameters, $K_{dc\_1}$ and $\tau_1$.

3. By identifying the controller gains $K_{p\_1}$ and $K_{i\_1}$, fit the obtained characteristic equation to the second-order standard form expressed below:

   $$s^2 + 2\zeta_1\omega_{n1}s + \omega_{n1}^2 = 0 \tag{3.12}$$

   Determine $K_{p\_1}$ and $K_{i_1}$ as functions of the parameters $\omega_{n1}$, $\zeta_1$, $K_{dc\_1}$, and $\tau_1$ using Equation 3.5.

4. Determine the numerical values for $K_{p\_1}$ and $K_{i\_1}$ in order for the tank 1 system to meet the closed-loop desired specifications, as previously stated.

# 3.3 Lab Experiments

## 3.3.1 Objectives

- Tune through pole placement the PI-plus-feedforward controller for the actual water level in tank 1 of the Coupled-Tank system.
- Implement the PI-plus-feedforward control loop for the actual Coupled-Tank's tank 1 level.
- Run the obtained PI-plus-feedforward level controller and compare the actual response against the controller design specifications.
- Run the system's simulation simultaneously, at every sampling period, in order to compare the actual and simulated level responses.

## 3.3.2 Tank 1 Level Control Simulation

**Experimental Setup**

The *s_tanks_1* Simulink® diagram shown in Figure 3.4 is used to perform tank 1 level control simulation exercises in this laboratory.

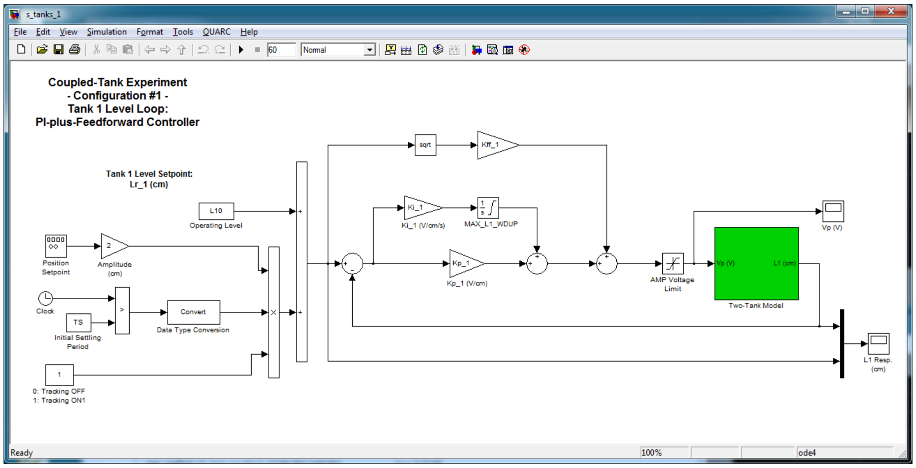


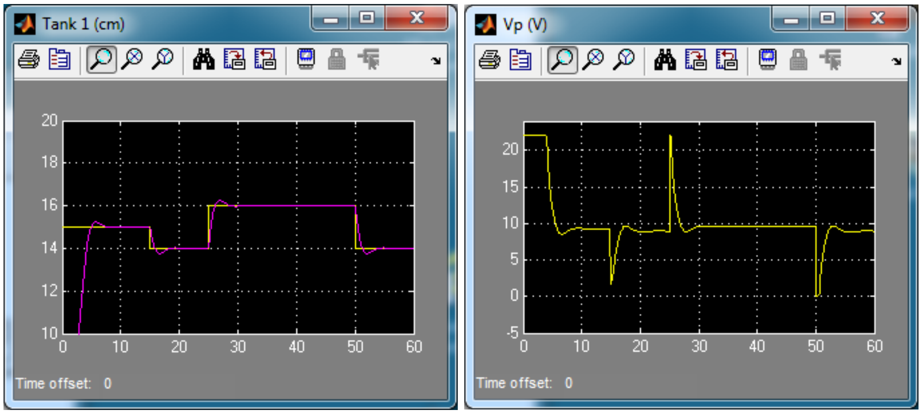
Figure 3.4: Simulink model used to simulate PI-FF control on Coupled Tanks system in configuration #1.

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

Follow this procedure:

1. Enter the proportional, integral, and feedforward gain control gains found in Section 3.2 in Matlab as *Kp_1*, *Ki_1*, and *Kff_1*.
2. To generate a step reference, go to the Signal Generator block and set it to the following:
    - Signal type = *square*
    - Amplitude = 1
    - Frequency = 0.02 Hz
3. Set the *Amplitude (cm)* gain block to 1 to generate a square wave goes between $\pm 1$ cm.

4. Open the pump voltage *Vp (V)* and tank 1 level response *Tank 1(cm)* scopes.
5. By default, there should be anti-windup on the Integrator block (i.e., just use the default Integrator block).
6. Start the simulation. By default, the simulation runs for 60 seconds. The scopes should be displaying responses similar to Figure 3.5. Note that in the *Tank 1 (cm)* scope, the yellow trace is the desired level while the purple trace is the simulated level.



(a) Tank 1 Level (b) Pump Voltage

Figure 3.5: Simulated closed-loop configuration #1 control response

7. Generate a Matlab® figure showing the *Simulated Tank 1* response and the pump voltage.

   **Data Saving**: After each simulation run, each scope automatically saves their response to a variable in the Matlab® workspace. The *Vp (V)* scope saves its response to the variable called data_Vp and the *Tank 1 (cm)* scope saves its data to the *data_L1* variable.

   - The *data_L1* variable has the following structure: *data_L1(:,1)* is the time vector, *data_L1(:,2)* is the setpoint, and *data_L1(:,3)* is the simulated level.
   - For the *data_Vp* variable, *data_Vp(:,1)* is the time and *data_Vp(:,2)* is the simulated pump voltage.

8. 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. Does the response satisfy the specifications given in Section 3.1.1?

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

### 3.3.3 Tank 1 Level Control Implementation

The q_tanks_1 Simulink diagram shown in Figure 3.6 is used to perform the tank 1 level control exercises in this laboratory. The *Coupled Tanks* subsystem contains QUARC® blocks that interface with the pump and pressure sensors of the Coupled Tanks system.

Note that a first-order low-pass filter with a cut-off frequency of 2.5 Hz is added to the output signal of the tank 1 level pressure sensor. This filter is necessary to attenuate the high-frequency noise content of the level measurement. Such a measurement noise is mostly created by the sensor's environment consisting of turbulent flow and circulating air bubbles. Although introducing a short delay in the signals, low-pass filtering allows for higher controller gains in the closed-loop system, and therefore for higher performance. Moreover, as a safety watchdog, the controller will stop if the water level in either tank 1 or tank 2 goes beyond 27 cm.

**Experimental Setup**

The *q_tanks_1* Simulink® diagram shown in Figure 3.6 will be used to run the PI+FF level control on the actual Coupled Tanks system.

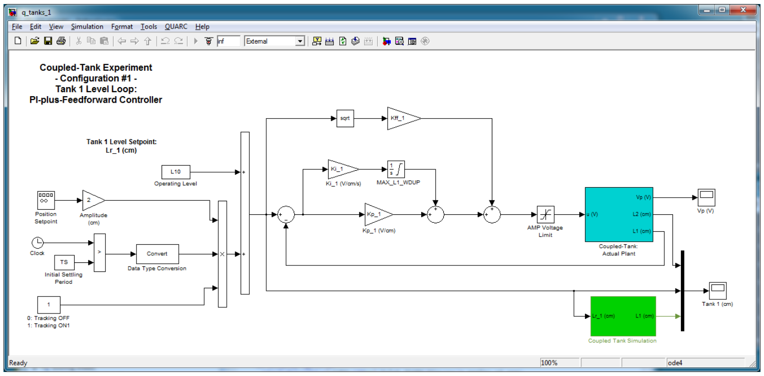


Figure 3.6: Simulink model used to run tank 1 level control on Coupled Tanks system.

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

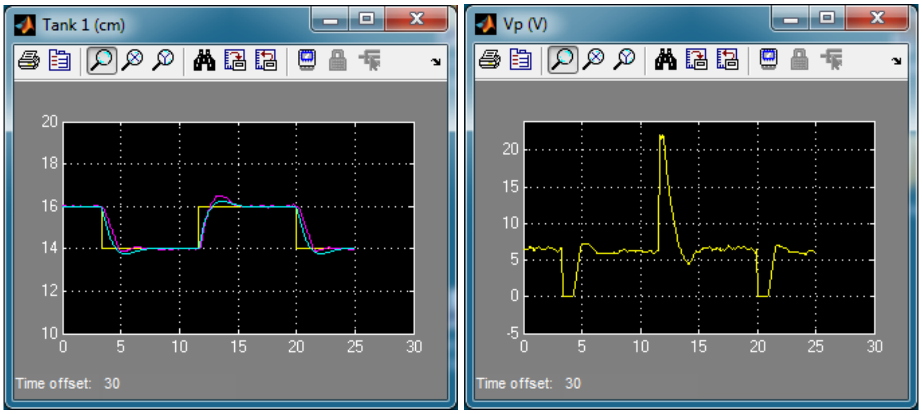
Follow this procedure:

1. Enter the proportional, integral, and feed forward control gains found in Section 3.2 in Matlab® as *Kp_1*, *Ki_1*, and *Kff_1*.
2. To generate a step reference, go to the Signal Generator block and set it to the following:
    - Signal type = *square*
    - Amplitude = 1
    - Frequency = 0.06 Hz
3. Set the *Amplitude (cm)* gain block to 1 to generate a square wave goes between $\pm 1$ cm.
4. Open the pump voltage *Vp (V)* and tank 1 level response *Tank 1(cm)* scopes.
5. By default, there should be anti-windup on the Integrator block (i.e., just use the default Integrator block).
6. In the Simulink diagram, go to QUARC | Build.
7. Click on QUARC | Start to run the controller. The pump should start running and filling up tank 1 to its operating level, $L_{10}$. After a settling delay, the water level in tank 1 should begin tracking the $\pm$1 cm square wave setpoint (about operating level $L_{10}$).
8. Generate a Matlab® figure showing the *Implemented Tank 1 Control* response and the input pump voltage.

   **Data Saving**: As in s_tanks_1.mdl, after each run each scope automatically saves their response to a variable in the Matlab® workspace.
9. Measure the steady-state error, the percent overshoot and the peak time of the response. Does the response satisfy the specifications given in Section 3.1.1? **Hint:** Use the Matlab® *ginput* command to take measurements off the figure.

## 3.4 Results

Fill out Table 3.1 with your answers from your control lab results - both simulation and implementation.



(a) Tank 1 Level

(b) Pump Voltage

Figure 3.7: Measured closed-loop tank 1 control response

| Description | Symbol | Value | Units |
|---|---|---|---|
| **Pre Lab Questions** | | | |
| *Tank 1 Control Gains* | | | |
| Feed Forward Control Gain | $K_{ff,1}$ | | V/$\sqrt{cm}$ |
| Proportional Control Gain | $k_{p,1}$ | | V/cm |
| Integral Control Gain | $k_{i,1}$ | | V/(cm-s) |
| **Tank 2 Control Simulation** | | | |
| Steady-state error | $e_{ss,1}$ | | cm |
| Settling time | $t_{s,1}$ | | s |
| Percent overshoot | $PO_1$ | | % |
| **Tank 2 Control Implementation** | | | |
| Steady-state error | $e_{ss,1}$ | | cm |
| Settling time | $t_{s,1}$ | | s |
| Percent overshoot | $PO_1$ | | % |

Table 3.1: Tank 1 Level Control Results

# 4 TANK 2 LEVEL CONTROL

## 4.1 Background

### 4.1.1 Specifications

In configuration #2, the pump feeds tank 1 and tank 1 feeds tank 2. The designed closed-loop system is to control the water level in tank 2 (i.e. the bottom tank) from the water flow coming out of tank 1, located above it. Similarly to configuration #1, the control scheme is based on a Proportional-plus-Integral-plus-Feedforward law.

In response to a desired $\pm$ 1 cm square wave level setpoint from tank 2 equilibrium level position, the water height behaviour should satisfy the following design performance requirements:

1. Tank 2 operating level at 15 cm: $L_{20} = 15$ cm.
2. Percent overshoot should be less than or equal to 10%: $PO_2 \leq 10.0$ %.
3. 2% settling time less than 20 seconds: $t_{s,2} \leq 20.0$ s.
4. No steady-state error: $e_{ss,2} = 0$ cm.

### 4.1.2 Tank 2 Level Controller Design: Pole Placement

For zero steady-state error, tank 1 water level is controlled by means of a Proportional-plus-Integral (PI) closed-loop scheme with the addition of a feedforward action, as illustrated in Figure 4.1, below.

In the block diagram depicted in Figure 4.1, the water level in tank 1 is controlled by means of the closed-loop system previously designed in Section 3.1. This is represented by the tank 1 closed-loop transfer function defined below:

$$T_1(s) = \frac{L_1(s)}{L_{r\_1}(s)} \tag{4.1}$$

Such a subsystem represents an inner (or nested) level loop. In order to achieve a good overall stability with such a configuration, the inner level loop (i.e. tank 1 closed-loop system) must be much faster than the outer level loop. This constraint is met by the previously stated controller design specifications, where $t_{s\_1} \leq t_{s\_2}$.

However for the sake of simplicity in the present analysis, the water level dynamics in tank 1 are neglected. Therefore, it is assumed hereafter that:

$$L_1(t) = L_{r\_1}(t) \qquad i.e. \qquad T_1(s) = 1 \tag{4.2}$$

Furthermore as depicted in Figure 4.1, the level feedforward action is characterized by:

$$L_{ff\_1} = K_{ff\_2} L_{r\_2} \tag{4.3}$$

and

$$L_1 = L_{11} + L_{ff\_1} \tag{4.4}$$

The level feedforward action, as seen in Figure 4.1, is necessary since the PI control system is only designed to compensate for small variations (a.k.a. disturbances) from the linearized operating point $L_{10}$, $L_{20}$. In other words, while the feedforward action compensates for the water withdrawal (due to gravity) through tank 2's bottom outlet orifice, the PI controller compensates for dynamic disturbances.

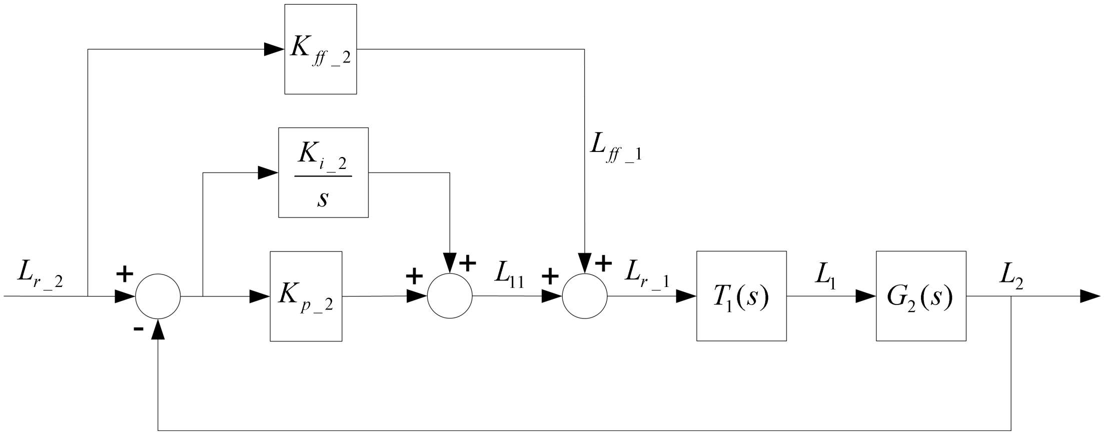


Figure 4.1: Tank 2 Water Level PI-plus-Feedforward Control Loop.

The open-loop transfer function $G_2(s)$ takes into account the dynamics of the tank 2 water level loop, as characterized by Equation 2.10. However, due to the presence of the feedforward loop and the simplifying assumption expressed by Equation 4.2, $G_2(s)$ can also be written as follows:

$$G_2(s) = \frac{L_2(s)}{L_1(s)} \tag{4.5}$$

## 4.2 Pre-Lab Questions

1. Analyze tank 2 water level closed-loop system at the static equilibrium point $(L_{10}, L_{20})$ and determine and evaluate the voltage feedforward gain, $K_{ff\_2}$, as defined by Equation 4.3.
2. Using tank 2 voltage-to-level transfer function $G_2(s)$ determined in Section 2 and the control scheme block diagram illustrated in Figure 4.1, derive the normalized characteristic equation of the water level closed-loop system.

   **Hint#1:** Block diagram reduction can be carried out.

   **Hint#2:** The system's normalized characteristic equation should be a function of the PI level controller gains, $K_{p\_2}$, and $K_{i\_2}$, and system's parameters, $K_{dc\_2}$ and $\tau_2$.
3. By identifying the controller gains $K_{p\_2}$ and $K_{i\_2}$, fit the obtained characteristic equation to the standard second-order equation: $s^2 + 2\zeta_2\omega_{n2}s + \omega_{n2}^2 = 0$. Determine $K_{p\_2}$ and $K_{i_2}$ as functions of the parameters $\omega_{n2}$, $\zeta_2$, $K_{dc\_2}$, and $\tau_2$.
4. Determine the numerical values for $K_{p\_2}$ and $K_{i\_2}$ in order for the tank 2 system to meet the closed-loop desired specifications, as previously stated.

## 4.3 Lab Experiments

### 4.3.1 Objectives

- Tune through pole placement the PI-plus-Feedforward controller for the actual water level of the Coupled-Tank system's tank 2.
- Implement the PI-plus-Feedforward control loop for the actual tank 2 water level.
- Run the obtained Feedforward-plus-PI level controller and compare the actual response against the controller design specifications.
- Run the system's simulation simultaneously, at every sampling period, in order to compare the actual and simulated level responses.
- Investigate the effect of the nested PI-plus-Feedforward level control loop implemented for tank 2.

### 4.3.2 Tank 2 Level Control Simulation

In this section you will simulate the tank 2 level control of the Coupled Tanks system. The two-tank dynamics are modeled using the Simulink blocks and controlled using the PI+FF controller described in Section 4.1. Our goals are to confirm that the desired response specifications are satisfied and to verify that the amplifier is not saturated.

**Experimental Setup**

The *s_tanks_2* Simulink® diagram shown in Figure 4.2 will be used to simulate the tank 2 level control response with the PI+FF controller used earlier in Section 4.1.

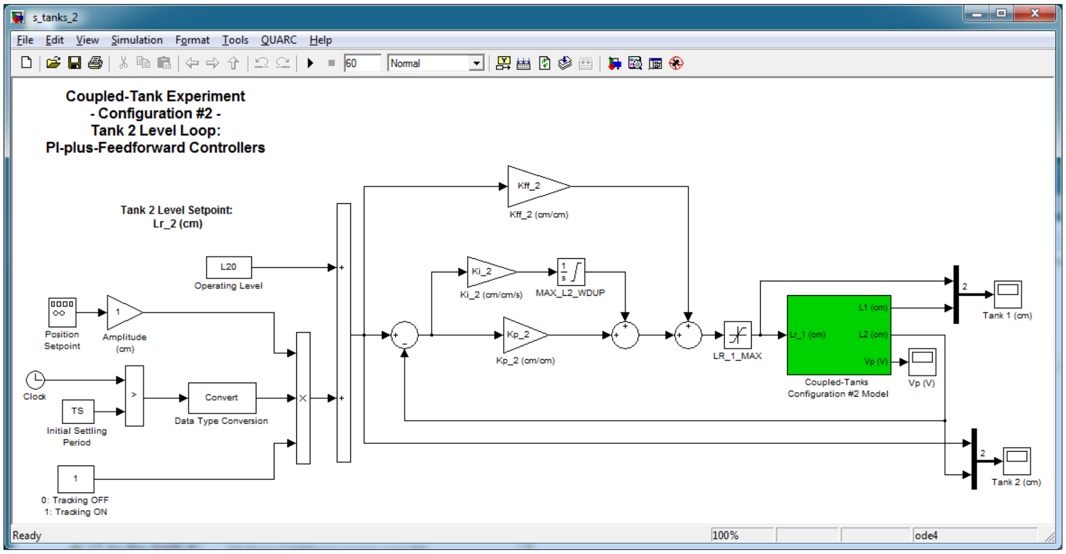
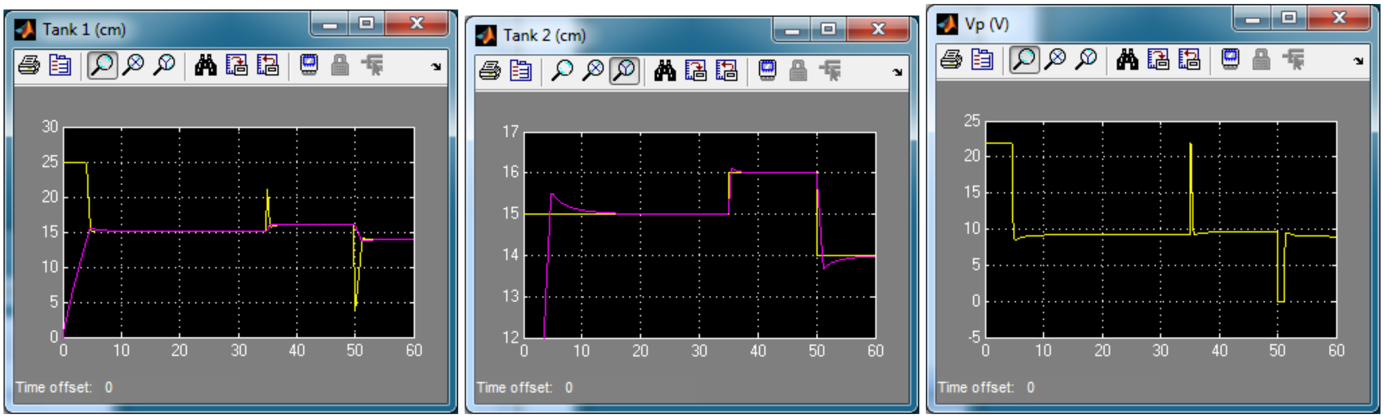


Figure 4.2: Simulink model used to simulate tank 2 level control response.

**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 you need to go to Section 5 to configure the lab files first.

1. Enter the proportional, integral, and feed-forward gains in Matlab found in the Tank 1 Control pre-lab questions in Section 3.2 as *Kp_1*, *Ki_1*, and *Kff_1*.
2. Enter the proportional, integral, and feed-forward control gains found in Section 4.2 in Matlab® as *Kp_2*, *Ki_2*, and *Kff_2*.

3. To generate a step reference, go to the *Position Setpoint* Signal Generator block and set it to the following:
    - Signal type = *square*
    - Amplitude = 1
    - Frequency = 0.02 Hz
4. Set the *Amplitude (cm)* gain block to $1$ to generate a step that goes between 14 and 15 mm (i.e., $\pm 1$ cm square wave with $L_{10} = 15$ cm operation point).
5. Open the *Tank 1 (cm)*, *Tank 2 (cm)*, and *Vp (V)* scopes.
6. Start the simulation. By default, the simulation runs for 120 seconds. The scopes should be displaying responses similar to Figure 4.3. Note that in the *Tank 1 (cm)* and *Tanks 2 (cm)* scopes, the yellow trace is the setpoint (or command) while the purple trace is the simulation.



(a) Tank 1 Level (b) Tank 2 Level (c) Pump Voltage

Figure 4.3: Simulated closed-loop tank 2 level control response.

7. Generate a Matlab® figure showing the *Simulated Configuration #2* response. Include both tank 1 and 2 level responses as well as the pump voltage.

   **Data Saving**: Similarly as with s_tanks_1, after each simulation run each scope automatically saves their response to a variable in the Matlab® workspace. The *Tank 2 (cm)* scope saves its response to the data_L2 variable. The *Tank 1 (cm)* scope saves its response to the variable called data_L1 and the *Pump Voltage (V)* scope saves its data to the *data_Vp* variable.
8. Measure the steady-state error, the percent overshoot and the settling time of the simulated response. Does the response satisfy the specifications given in Section 2.1.4? **Hint:** Use the Matlab® *ginput* command to take measurements off the figure.

### 4.3.3 Tank 2 Level Control Implementation

The q_tanks_2 Simulink diagram shown in Figure 4.4 is used to run the Tank 2 Level control presented in Section 4.1 on the Coupled Tanks system (i.e., when set up in Configuration #2). The *Tank 1 Inner Loop* subsystem contains the PI+FF control used previously in Section 3.3.3 as well as the *Coupled Tanks* subsystem, which contains QUARC® blocks that interface with the pump and pressure sensors of the Coupled Tanks system.

#### Experimental Setup

The *q_tanks_2* Simulink® diagram shown in Figure 4.4 will be used to run the feed-forward and PI level control on the actual Coupled Tanks system.

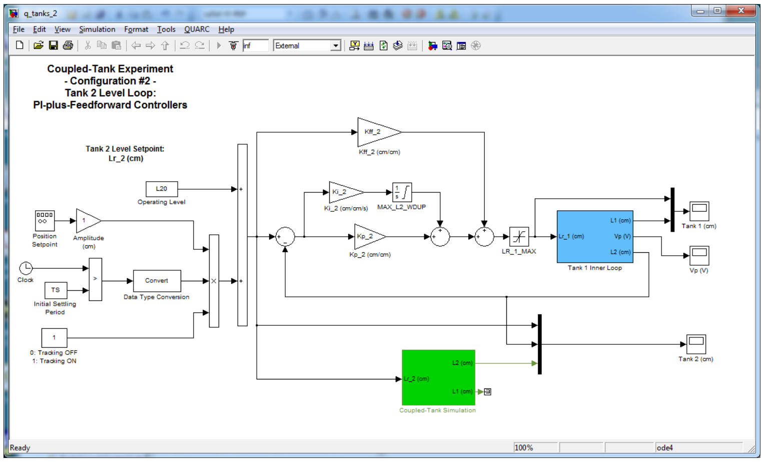


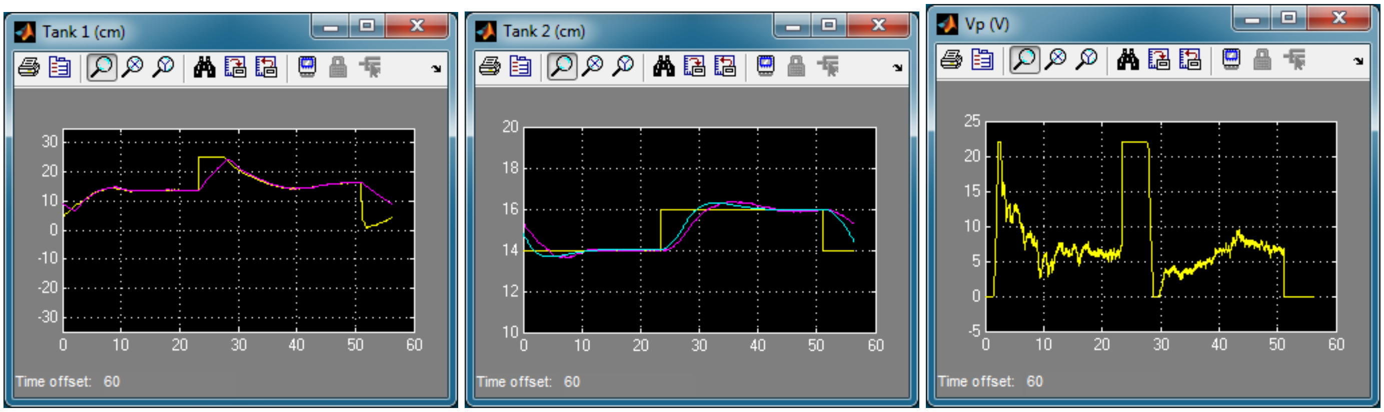
Figure 4.4: Simulink model used to run tank 2 level control on Coupled Tanks system.

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

Follow this procedure:

1. Enter the proportional, integral, and feed-forward gains in Matlab used in the Tank 1 Control simulation in Section 3.3.2 as *Kp_1*, *Ki_1*, and *Kff_1*.
2. Enter the proportional, integral, and feed-forward control gains found in Section 4.2 in Matlab® as *Kp_2*, *Ki_2*, and *Kff_2*.
3. To generate a step reference, go to the *Position Setpoint* Signal Generator block and set it to the following:
    - Signal type = *square*
    - Amplitude = 1
    - Frequency = 0.02 Hz
4. Set the *Amplitude (cm)* gain block to $1$ to generate a step that goes between 14 and 15 mm (i.e., $\pm 1$ cm square wave with $L_{10} = 15$ cm operation point).
5. Open the *Tank 1 (cm)*, *Tank 2 (cm)*, and *Vp (V)* scopes.
6. In the Simulink diagram, go to QUARC | Build.
7. Click on QUARC | Start to run the controller. The level in tank 2 will first stabilize to the operating point tank 2 operating point. After the settling period, the $\pm$1 cm step will start. The scopes should be displaying responses similar to Figure 4.5 (after the settling period).
8. Generate a Matlab®figure showing the *Implemented Tank 2 Level Control* response, i.e., the tank 1 and 2 levels as well as the pump voltage.

    **Data Saving**: As with s_tanks_2, after each run the scopes automatically save their response to a variable in the Matlab® workspace. The *Tank 1 (cm)* and *Tank 2 (cm)* scopes save their response to the data_L1 and data_L2 variables. The *Pump Voltage (V)* scope saves its response to the variable called data_Vp.
9. Measure the steady-state error, the percent overshoot and the peak time of the response obtained on the actual system. Does the Tank 2 response satisfy the specifications given in Section 2.1.4?



(a) Tank 1 Level (b) Tank 2 Level (c) Pump Voltage

Figure 4.5: Typical response when controlling tank 2 level.

## 4.4 Results

Fill out Table 4.1 with your answers from your control lab results - both simulation and implementation.

| Description | Symbol | Value | Units |
|---|---|---|---|
| **Pre Lab Questions** | | | |
| *Tank 1 Control Gains* | | | |
| Proportional Control Gain | $k_{p,1}$ | | V/cm |
| Integral Control Gain | $k_{i,1}$ | | V/(cm-s) |
| Feed Forward Control Gain | $K_{ff,1}$ | | V/$\sqrt{cm}$ |
| *Tank 2 Control Gains* | | | |
| Proportional Control Gain | $k_{p,2}$ | | cm/cm |
| Integral Control Gain | $k_{i,2}$ | | 1/s |
| Feed Forward Control Gain | $K_{ff,2}$ | | cm/cm |
| **Tank 2 Control Simulation** | | | |
| Steady-state error | $e_{ss}$ | | cm |
| Settling time | $t_s$ | | s |
| Percent overshoot | PO | | % |
| **Tank 2 Control Implementation** | | | |
| Steady-state error | $e_{ss}$ | | cm |
| Settling time | $t_s$ | | s |
| Percent overshoot | PO | | % |

Table 4.1: Tank 2 Level Control Results Results

# 5 SYSTEM REQUIREMENTS

### Required Software

- Microsoft Visual Studio (MS VS)
- Matlab® with Simulink®, Real-Time Workshop, and the Control System Toolbox
- QUARC®

See the QUARC® software compatibility chart in [3] to see what versions of MS VS and Matlab are compatible with your version of QUARC and for what OS.

### Required Hardware

- Data acquisition (DAQ) device that is compatible with QUARC®. This includes Quanser DAQ boards such as Q2-USB, Q8-USB, QPID, and QPIDe and some National Instruments DAQ devices. For a full listing of compliant DAQ cards, see Reference [1].
- Quanser Coupled Tanks.
- Quanser VoltPAQ-X1 power amplifier, or equivalent.

### Before Starting Lab

Before you begin this laboratory make sure:

- QUARC®is installed on your PC, as described in [2].
- DAQ device has been successfully tested (e.g., using the test software in the Quick Start Guide or the *QUARC Analog Loopback Demo*).
- Coupled Tanks and amplifier are connected to your DAQ board as described Reference [5].

## 5.1 Overview of Files

| File Name | Description |
|---|---|
| Coupled-Tanks User Manual.pdf | This manual describes the hardware of the Coupled Tanks system and explains how to setup and wire the system for the experiments. |
| Coupled-Tanks Workbook (Student).pdf | This laboratory guide contains pre-lab questions and lab experiments demonstrating how to design and implement controllers for on the Coupled Tanks plant using QUARC®. |
| setup_lab_tanks.m | The main Matlab script that sets the Coupled Tanks control and model parameters. Run this file only to setup the laboratory. |
| config_coupled_tanks.m | Returns the Coupled Tanks system parameters as well as the amplifier limits VMAX_AMP and IMAX_AMP. |
| s_tanks_1.mdl | Simulink file that simulates the Tank 1 Level Control, i.e., Coupled Tanks Configuration #1 system. |
| s_tanks_2.mdl | Simulink file that simulates the Tank 2 Level Control, i.e., Coupled Tanks Configuration #2 system. |
| s_tanks_3.mdl | Simulink file that simulates the Tank 2 Level Control when the Coupled Tanks is in Configuration #3. Note that there are no instructions on how ot use any of the Configuration #3 files. |
| q_tanks_1.mdl | Simulink file that implements the PI+FF controller on the Coupled Tanks system using QUARC® when setup in Configuration #1. |
| q_tanks_2.mdl | Simulink file that implements the PI+FF controller on the Coupled Tanks system using QUARC® when setup in Configuration #2. |
| q_tanks_3.mdl | Simulink file that implements the PI+FF controller on the Coupled Tanks system using QUARC® when setup in Configuration #3. Note that there are no instructions on how ot use any of the Configuration #3 files. |

Table 5.1: Files supplied with the Coupled Tanks

## 5.2 Setup for Tanks 1 Control Simulation

Before beginning the in-lab procedure outlined in Section 3.3.2, the s_tanks_1 Simulink diagram and the setup_lab_tanks.m script must be configured.

Follow these steps:

1. Load the Matlab® software.
2. Browse through the *Current Directory* window in Matlab and find the folder that contains the file *setup_lab_tanks.m*.
3. Open the *setup_lab_tanks.m* script.
4. **Configure setup_lab_tanks.mscript**: Make sure the script is setup to match your system configuration:
    - K_AMP to 3 (unless your amplifier gain is different)
    - AMP_TYPE to your amplifier type (e.g., VoltPAQ).
    - CONTROLLER_TYPE to 'MANUAL'.

5. Run setup_lab_tanks.m to setup the Matlab workspace.
6. Enter the PI+FF control gains you found in the Pre-Lab Questions Section 3.2 in the Matlab as the variables: Kp_1, Ki_1, Kff_1.
7. Open the *s_tanks_1.mdl* Simulink diagram, shown in Figure 3.4.

## 5.3 Setup for Tanks 2 Control Simulation

Before beginning the in-lab procedure outlined in Section 4.3.2, the s_tanks_2 Simulink diagram and the setup_lab_tanks.m script must be configured.

Follow these steps:

1. Go through the steps outlined in Section 5.2 to configure the setup_lab_tanks.m script properly.
2. Run setup_lab_tanks.m to setup the Matlab workspace.
3. Enter the proportional, integral, and feed-forward gains in Matlab used in the Tank 1 Control simulation in Section 3.3.2 as *Kp_1*, *Ki_1*, and *Kff_1*.
4. Enter the proportional, integral, and feed-forward control gains found in Section 4.2 in Matlab® as *Kp_2*, *Ki_2*, and *Kff_2*.
5. Open the *s_tanks_2.mdl* Simulink diagram, shown in Figure 4.2.

## 5.4 Setup for Implementing Tank 1 Control

Before performing the in-lab exercises in Section 3.3.3, the q_tanks_1 Simulink diagram and the setup_lab_tanks.m script must be configured.

Follow these steps to get the system ready for this lab:

1. Go through the Coupled Tanks User Manual ([5]) to set up the system:
    - Hardware set up and connections.
    - Make sure the pressure sensors of the system have been **calibrated**.
    - Set up the Coupled Tanks in Configuration #1 (i.e., tank 1 only).
2. If using the VoltPAQ-X1, **make sure the Gain switch is set to 3**.
3. Configure and run setup_lab_tanks.m as explained in Section 5.2.
4. Open the *q_tanks_1.mdl* Simulink diagram, shown in Figure 3.6.
5. **Configure DAQ:** Ensure the HIL Initialize block in the Simulink model is configured for the DAQ device that is installed in your system. See Reference [1] for more information on configuring the HIL Initialize block.

## 5.5 Setup for Implementing Tank 2 Level Control

Before performing the in-lab exercises in Section 4.3.3, the q_tanks_2 Simulink diagram and the setup_lab_tanks.m script must be configured.

Follow these steps to get the system ready for this lab:

1. Go through the Coupled Tanks User Manual ([5]) to set up the system:
    - Hardware set up and connections.
    - Make sure the pressure sensors of the system have been **calibrated**.
    - Set up the Coupled Tanks in Configuration #2 (i.e., tank 1 feeds into tank 2).
2. If using the VoltPAQ-X1, **make sure the Gain switch is set to 3**.
3. Configure and run setup_lab_tanks.m as explained in Section 5.2.
4. Open the *q_tanks_2.mdl* Simulink diagram, shown in Figure 4.4.
5. **Configure DAQ:** Ensure the HIL Initialize block in the Simulink model is configured for the DAQ device that is installed in your system. See Reference [1] for more information on configuring the HIL Initialize block.

# 6 LAB REPORT

This laboratory contains two groups of experiments, namely,

1. Tank 1 Level control, and
2. Tank 2 Level control.

For each experiment, follow the outline corresponding to that experiment to build the *content* of your report. Also, in Section 6.3 you can find some basic tips for the *format* of your report.

## 6.1 Template for Tank 1 Level Control Report

**I. PROCEDURE**

1. *Simulation*
    - Briefly describe the main goal of the simulation.
    - Briefly describe the simulation procedure in Step 7 in Section 3.3.2.
2. *Implementation*
    - Briefly describe the main goal of this experiment.
    - Briefly describe the experimental procedure in Step 8 in Section 3.3.3.

**II. RESULTS**
Do not interpret or analyze the data in this section. Just provide the results.

1. Response plot from step 7 in Section 3.3.2, *Tank1 level control simulation*.
2. Response plot from step 8 in Section 3.3.3, *Tank 1 level control implementation*.
3. Provide applicable data collected in this laboratory (from Table 3.1).

**III. ANALYSIS**
Provide details of your calculations (methods used) for analysis for each of the following:

1. Peak time, percent overshoot, steady-state error, and input voltage in Step 8 in Section 3.3.2.
2. Peak time, percent overshoot, steady-state error, and input voltage in Step 9 in Section 3.3.3.

**IV. CONCLUSIONS**
Interpret your results to arrive at logical conclusions for the following:

1. Whether the controller meets the specifications in Step 8 in Section 3.3.2, *Tank1 level control simulation*.
2. Whether the controller meets the specifications in Step 9 in Section 3.3.3, *Tank1 level control implementation*.

## 6.2 Template for Tank 2 Level Control Report

### I. PROCEDURE

1. *Simulation*
   - Briefly describe the main goal of the simulation.
   - Briefly describe the simulation procedure in Step 7 in Section 4.3.2.
2. *Implementation*
   - Briefly describe the main goal of this experiment.
   - Briefly describe the experimental procedure in Step 8 in Section 4.3.3.

### II. RESULTS

Do not interpret or analyze the data in this section. Just provide the results.

1. Response plot from step 7 in Section 4.3.2, *Tank2 level control simulation*.
2. Response plot from step 8 in Section 4.3.3, *Tank2 level control implementation*.
3. Provide applicable data collected in this laboratory (from Table 4.1).

### III. ANALYSIS

Provide details of your calculations (methods used) for analysis for each of the following:

1. Peak time, percent overshoot, steady-state error, and input voltage in Step 8 in Section 4.3.2.
2. Peak time, percent overshoot, steady-state error, and input voltage in Step 9 in Section 4.3.3.

### IV. CONCLUSIONS

Interpret your results to arrive at logical conclusions for the following:

1. Whether the controller meets the specifications in Step 9 in Section 4.3.3, *Tank2 level control implementation*.

## 6.3 Tips for Report Format

### PROFESSIONAL APPEARANCE

- Has cover page with all necessary details (title, course, student name(s), etc.)
- Each of the required sections is completed (Procedure, Results, Analysis and Conclusions).
- Typed.
- All grammar/spelling correct.
- Report layout is neat.
- Does not exceed specified maximum page limit, if any.
- Pages are numbered.
- Equations are consecutively numbered.
- Figures are numbered, axes have labels, each figure has a descriptive caption.
- Tables are numbered, they include labels, each table has a descriptive caption.
- Data are presented in a useful format (graphs, numerical, table, charts, diagrams).
- No hand drawn sketches/diagrams.
- References are cited using correct format.

# REFERENCES

[1] Quanser Inc. *QUARC User Manual*.

[2] Quanser Inc. *QUARC Installation Guide*, 2009.

[3] Quanser Inc. *QUARC Compatibility Table*, 2010.

[4] Quanser Inc. *Coupled Tank User Manual*, 2012.

## Process control plants for teaching and research

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**Magnetic Levitation**

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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