A Multivariable Hot and Cold Water Tank for an Undergraduate Control Engineering Laboratory

Haryana Yosef Thomas, Calvin College

My name is Haryana Thomas and I’m a chemical engineering undergraduate student at Calvin college. After graduation, I hope to go to graduate school to pursue a PHD in process systems engineering.

Mr. Charles E. Holwerda, Calvin College
Dr. Jeremy VanAntwerp, Calvin College

Professor of Engineering at Calvin College.
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The main purpose of this paper is to describe the construction of a bench-scale cyberphysical system for use as a lab experiment. Cyberphysical systems have a “cyber” layer that handles communication and control of “physical” elements in the real world. In this case, the physical system mixes hot and cold running water in a clear plastic tank with an open drain. The cyber layer measures the incoming water temperature in the hot and cold lines, the incoming water flow rates, and the height and temperature of water in the tank. There are control valves on the hot- and cold-water lines that can adjust these flow rates. A data-acquisition system communicates to a control computer over an ethernet connection.

The second contribution of this paper is to describe the software selection and design of the cyber layer. This is intended as a guide or example for other instructors who want to create an apparatus with communication and control capability.

Cyberphysical systems have been a focus for research in the engineering community recently, in part because of the promise these systems offer for improving quality-of-life, and in part due to justified fears that cyberphysical systems are too vulnerable to malicious attack through internet-connected cyber layers [1]. Researchers seek to understand the complex interactions of the “cyber” and the “physical” to design methods to detect and thwart cyberphysical attack. The February 2015 issue of IEEE Control Systems [2] has several articles that outline the challenges and opportunities in the area of control of networked systems and offers a good tutorial introduction to cyberphysical security. However, despite the large amount of research, there are few undergraduate laboratory experiments dealing with cyberphysical systems that have been described (see [3] and [4] as notable exceptions). Of the few that exist, many (or most) have minimal physical dynamics, such as [5], [6], [7], and [8].

Likewise, relatively few undergraduate process control laboratory experiments are multivariable. (For some example exceptions, see [9], [10], [11], [12], [13], and [14]). Furthermore, although model predictive control (MPC) is an excellent way to control complex multivariable processes, it is generally not covered much at the undergraduate level and few lab experiments are focused on MPC. Exceptions are [15], [16], [17], and [18].

In contrast, the apparatus described in this paper is multivariable and is set up to be amenable to MPC, among other control configurations. The system can be used in a variety of ways. Most obviously, this setup lends itself to multiple-input, multiple-output (MIMO) process control experiments. Also, and perhaps more subtly, it can be used to compare the performance of different control architectures. A basic fluid-mechanics lab experiment is also described. Finally, the apparatus can be used as a platform for investigating the security of cyberphysical systems.

Section 1 gives a complete description of the lab apparatus. The physical components are described in section 1.1. The next two subsections describe the electronic and software components of the system. The data acquisition and command hardware is centered around a National Instruments (NI) compact data acquisition board (c-DAQ). One of the design objectives
for the software environment is to allow students to implement a variety of different control methods, such as independent PID control loops (that is, a decentralized control strategy), cascade control, and/or multivariable model predictive control. Section one concludes with a mathematical model of the process, which shows that the process is nonlinear.

Section 2 describes several different possible student experiments with this apparatus and shows example experimental results. Section 3 presents student responses. The paper concludes with some overall observations and suggestions to improve the design.

1. The Lab Apparatus

This section describes the different components of the lab apparatus. This apparatus (both the cyber and physical) was constructed to teach advanced control topics to undergraduates in a senior-level process control lab.

1.1. Lab Apparatus Hardware

The lab apparatus is shown in Figure 1 and component specifications are given in Table 1. Domestic hot and cold water lines come in from the left-hand side. The hot and cold water flow rates are set by control valves (marked “a” in Figure 1) and the temperature of the incoming water is measured by in-line thermocouples (marked “b” in Figure 1). Water flow rates are measured by flow meters (marked “c” in Figure 1). The reason for having both control valves and flow meters is that it allows both higher precision in setting flow rates and it enables more sophisticated control architectures, such as cascade control. The hot and cold water flows are combined (at point “e” a thermocouple measures the temperature of the combined streams) and the water goes into a clear plastic tank (marked “d” in Figure 1). A small opening in the bottom of the tank allows water to constantly flow out of the tank. Water temperature in the tank is obtained by a thermocouple (marked “e” in Figure 1) and the water level in the tank is obtained from a pressure transducer (marked “f” in Figure 1). A float-type valve (marked “g” in Figure 1) prevents the tank from being overfilled.
Figure 1. A picture of the completed apparatus. a) Hot and cold water control valves. b) Hot and cold water temperature measurement. c) Hot and cold flow rate measurements. d) Tank. e) Two thermocouples: one at the mixing point and one extending down into the tank. f) Tank pressure transducer.

Table 1. Lab apparatus major hardware details.

<table>
<thead>
<tr>
<th>Component (label in Figure 1)</th>
<th>Specification</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control valves (a)</td>
<td>Hass Manufacturing</td>
<td>$870 each*</td>
</tr>
<tr>
<td></td>
<td>Model number ECV-250B-4X</td>
<td></td>
</tr>
<tr>
<td>Thermocouples (b,e)</td>
<td>Omega TC-K-NPT-U-72</td>
<td>$46.50 each</td>
</tr>
<tr>
<td>Flow meters (c)</td>
<td>Proteus Industries Inc. 8000 Series  # 08004BN06 (0.06 - 0.6 gal/min)</td>
<td>$325 each</td>
</tr>
<tr>
<td>Tank (d)</td>
<td>6.5 inch OD polycarbonate cylinder, 15” tall</td>
<td>N/A</td>
</tr>
<tr>
<td>Thermocouple (e)</td>
<td>Omega TJ80-CASS-14U-18-BX</td>
<td>$61.50</td>
</tr>
<tr>
<td>Pressure transducer (f)</td>
<td>Impress Sensors</td>
<td>$225</td>
</tr>
<tr>
<td></td>
<td>IMP-LR-G0050-5A4-BCV-00-000</td>
<td></td>
</tr>
<tr>
<td>Float valve (g)</td>
<td>Hudson Valve</td>
<td>$26</td>
</tr>
<tr>
<td></td>
<td>¼” V-QTR</td>
<td></td>
</tr>
</tbody>
</table>

* The control valves were surplus/salvage donated by Pfizer, Inc; hence the Pfizer logo in Figure 1.

1.2. Data-Acquisition Electronics

A close-up view of the data-acquisition hardware is shown in Figure 2 with specifications given in Table 2.
**Figure 2. Data acquisition hardware.**

**Table 2. Lab apparatus major data-acquisition hardware details.**

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chassis</td>
<td>National Instruments cDAQ 9185</td>
<td>$1025</td>
</tr>
<tr>
<td>Thermocouple module</td>
<td>National Instruments 9211</td>
<td>$396</td>
</tr>
<tr>
<td>Analog input module</td>
<td>National Instruments 9203</td>
<td>$592</td>
</tr>
<tr>
<td>Analog output module</td>
<td>National Instruments 9265</td>
<td>$419</td>
</tr>
<tr>
<td>Power supply</td>
<td>IDEC PS5R-VF24</td>
<td>$136.50</td>
</tr>
</tbody>
</table>

The data-acquisition hardware communicates the measurements and receives input commands over an ethernet network. There are four thermocouple measurements: one each on the hot and cold water, one on the combined inlet flow, and one in the tank. There are three analog (4-20mA) inputs (that is, measurements): the two incoming water flow rates and the pressure transducer that gives the height of water in the tank. Finally, there are two analog 4-20 mA outputs: the two control valves. For the lab apparatus described here, the chassis communicates over an ethernet connection to a control computer, details of which are given in the next section.

There were two options for ethernet-enabled cDAQ chassis: the 9184 and 9185. The 9184 was marked as a “Mature” product, meaning it is near the end of its production life. The 9185 has more features at a lower price, and the 9184 is not recommended for new designs (see [http://www.ni.com/life-cycle/hardware.htm](http://www.ni.com/life-cycle/hardware.htm)). Because we were building a new device that we wished to use for a long time, and to save money, we opted for the 9185. This led to software issues discussed below.

**1.3. Lab Apparatus Software Environment**

Labview is a popular software interface for lab data acquisition. However, Matlab/Simulink are more popular for control courses. We wished to create a “sandbox” platform so that students could easily experiment with many different control designs for controlling this process. We wished to eliminate them having to learn a second (new) software. For these reasons, Matlab/Simulink was chosen over Labview for the software environment for this experiment. Unfortunately, as of the 2019a version, Mathworks does not support the 9185 cDAQ chassis, only the 9184 version. Also, the 9203 and 9265 modules are only supported
in Matlab, not Simulink. For testing purposes, we were able to create work arounds with function blocks in Simulink for some of the variables we wanted to use. Hopefully, a future Matlab release will contain support for this newer generation of hardware.

1.4 Mathematical model of the process

The differential equations that describe the behaviour of the water in the tank are

\[ A \frac{dh}{dt} = q_{cold} + q_{hot} - C_v g h^{0.5}, \]  
\[ \frac{dT_{tank}}{dt} = q_{cold} T_{cold} + q_{hot} T_{hot} - C_v g h^{0.5} T_{tank}, \]

where \( A \) is the cross-sectional area of the tank; \( h \) is the height of water in the tank; \( t \) is time; \( q_{cold} \) and \( q_{hot} \) are the cold and hot water volumetric flow rates, respectively; \( g \) is the gravitational constant; \( C_v \) is the valve coefficient of the drain hole at the bottom of the tank; and \( T_{tank}, T_{cold}, \) and \( T_{hot} \) are the temperatures of the water in the tank, the cold water inlet stream, and the hot water inlet stream, respectively. Density and heat capacity of water are assumed to be constant over the temperature range of interest. Notice that both equations in this coupled set of differential equations are nonlinear because of the square-root dependence of the outlet flow rate on height and the fact that last term in (2) contains the product of the height and tank temperature.

Domestic hot and cold water temperatures are expected to drift a little over time as the pipes leading to the apparatus heat up or cool down. Likewise, even for a fixed inlet valve position, the incoming hot and cold water flow rates may fluctuate due to transients in the pressure of the pipes supplying the apparatus. These drifts and fluctuations are disturbances that the control system must reject.
2. Lab experiments
This section describes three of the many possible student lab experiments that could be performed with this apparatus, from the very basic to the very advanced.

2.1. Valve coefficient
Flow (q) through a constriction is proportional to the square root of the pressure drop (ΔP) across the constriction
\[ q = C_v \Delta P^{0.5}, \] (3)
where \( C_v \) is a constant (see [19], eq. 2.3.3). Water is allowed to drain from the tank of the apparatus through a small hole (the constriction) and the pressure drop across the constriction is proportional to the height of water in the tank. The constant \( C_v \) can be determined by plotting the flow rate as a function of the height of water in the tank. Since the apparatus is designed to operate under closed-loop control, water depth can be set and maintained at a constant height automatically. See Figure 3 for a sample student result.

![Graph showing flow rate vs. tank head](image)

*Figure 3. Sample student result for draining water from the tank of the lab apparatus.*

2.2. Multiple-input, multiple-output control performance with different control architectures
Undergraduate control courses tend to emphasize a single-input, single-output (SISO) perspective. However, in many industrial applications, processes and plants have significant interactions between measured variables, which means a multiple-input, multiple-output (MIMO) approach is more appropriate. Consequently, it is beneficial for students to have a good understanding of the different types of MIMO control. This section describes a MIMO control experiment using the apparatus described in section 1 for an undergraduate laboratory course in control engineering. The objective is for students to compare different types of controllers and different control architectures for their ability to control the level and temperature of the water in the tank independently. There are a great number of possible control strategies; three example control strategies are presented in the next three sections.

2.2.1. Decentralized PID control
Using a single process input to control a single output for a MIMO process is known as a decentralized control strategy. For a 2-input, 2-output process, there are two possible variable pairings: either the hot water flow rate is used to control the height of water in
the tank and the cold water flow rate is adjusted to control the temperature in the tank, or vice versa. In this example, the first pairing is used. The control architecture is shown in Figure 4. The most widely used controller is the proportional-integral-derivative (PID) controller. This example uses two PID controllers.

![Figure 4. Independent SISO PID loops (decentralized control) for the lab apparatus.](image)

Two independent PID controllers can’t control both variables simultaneously. A pairing that controls height with the cold water flow rate and temperature with the hot water flow rate would fall short in a similar way to the results shown here.
2.2.2. Cascade control and decoupling

Notice the oscillations in the right-hand side of Figure 5. This is one of the drawbacks of having the height controller act directly on the control valve. The height controller adjusts the valve, for instance by increasing percent open to raise the height. However, until the height in the tank exceeds the setpoint, the controller doesn’t know that it has opened the valve too much. An alternative is to use a cascade control structure, in which the height control specifies the hot water flow rate and another controller (called the slave controller) uses the hot water flow rate measurement to adjust the control valve to obtain the specified flow rate. A similar cascade structure can be used for the cold water flow rate. This structure reduces the time delay between flow adjustment and measurement and so improves control performance. Results for this case are omitted for brevity.

Decouplers can be designed to improve the performance of decentralized control loops. Again, results are omitted for brevity.

2.2.3. Model predictive control

Rather than just use single-loop pairings, a full MIMO controller can coordinate the different input variables to achieve the overall control objectives. Model predictive control (MPC) is an easy-to-implement-in-Simulink MIMO controller that has the added benefit of seamlessly handling constraints on process inputs – in this case, the fact that valves can’t open more than 100% nor can they have negative flow rates. Figure 6 shows a model predictive controller arrangement and Figure 7 shows some example results.

![Diagram](image)

*Figure 6. Model predictive control applied to the MIMO height and temperature control problem.*
2.3. Cyberphysical security

The need for security and control of systems that operate over networks is increasingly being recognized as a critical challenge. For instance, the classical laboratory quadruple-tank process [2] is analyzed for cyberphysical security in [3].

This section describes a student exercise appropriate for an advanced control course or a course dedicated to cyberphysical systems. Students are divided into two teams. The objective of the red team is to get the tank to overflow (represented by raising the water level in the tank to the point where the float valve shuts off the flow of water into the tank). The blue team must design control systems to keep the water level and temperature at the desired values, for instance, half full and 35°C. The red team does not get to interfere with the signals sent to the control valves (known as an input attack) but may send the controller one or more false measurement signals (known as a measurement attack).

3. Concluding Thoughts and Recommendations for Improvement

Students will use the new apparatus for the first time at the end of the spring semester 2019. Hopefully, this will allow including some student responses and comments in the final paper. This will be the first “hands on” process control experiment at our institution, so the students’ reactions to the difference between “real” experiments and simulations will be interesting.

In testing, a few design flaws have become evident. Copper piping was used for the apparatus to make it as durable as possible. The hot and cold water pipes join in a tee (near point “e” in Figure 1) prior to entering the tank so that temperature of the combined stream could be measured, which is necessary for some of the advanced control experiments that were planned. Unfortunately, after long periods of operation with one flow rate higher than the other, heat conducted through the metal pipes either chills the hot water thermocouple or heats the cold water thermocouple giving an inaccurate reading on the temperature of the stream with the lower
flow rate. Likewise, with unequal flow rates, the side with the greater flow rate creates a back pressure on the other stream, making low flow rates difficult to achieve. Both problems would be avoided by having the hot and cold water streams enter the tank separately. We may modify the apparatus to make this change. Lastly, the analog input and output modules were wired with unshielded wire, which gives a noisier signal than we’d like for the flow rate measurements and the height in the tank (via the pressure transducer). This does not seem to cause issues for the control valve outputs, but we would recommend using shielded wires on these measurements.

This paper gives details of construction and operation for a new lab apparatus that is suitable for undergraduate experiments in fluid mechanics, process control, and secure operation of cyberphysical systems. Hopefully, other instructors will be able to benefit from our experience using this equipment.

References


