A Flexible Multivariable Experimental Air Tank System for Process Control Education

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Abstract

This paper presents an industrially relevant multivariable experimental air pressure tank system which has been developed at the University of South Carolina for process control education. Inspired by experimental systems for liquid level modeling and control of a four-tank system [1, 2, 3, 4], this pressure control apparatus is quite flexible. It offers a wide variety of uses for both educational and research purposes, and it does so at moderate expense. As opposed to liquid level systems, pressure differences in the system drive the flow, removing limitations in system flexibility associated with gravity driven liquid systems. The four tank system can be configured to exhibit a multivariable right-half plane zero, demonstrating advanced concepts of input directionality and control limitations. A detailed description of the system and a model based on fundamental principles is provided. The current system allows for a computer interface to both MATLAB/Simulink [5] and LabView [6].

1 Introduction

Process control methods provide a fundamental technological basis for modern day chemical process operations. Process control education at the undergraduate level is often a difficult task due to the significant theoretical content of courses. Additionally, undergraduate students typically have limited experience with dynamic systems as many undergraduate engineering courses assume steady state operation. Using hands on experimental laboratory closely tied to the traditional process control lecture course allows students to see application to real world systems, justifying and motivating the theoretical content of the lecture course. Experimental labs for undergraduate education have been shown to be beneficial to the educational process [7, 8, 9, 10], especially when group learning techniques are applied [11, 12]. A variety of schools have developed process control experimental systems [13, 14, 15].

When developing process control dynamic experiments, one should examine a variety of considerations. Ideally, the system should be safe to use, industrially relevant, relatively inexpensive, with flexible configuration options. The system should be of a moderate level of complexity; simple systems may be too trivial to motivate students while a full-scale industrial process may be overwhelming. Dynamic experiments should help to reinforce and demonstrate textbook theory [16, 17, 18, 19, 20, 21]. Additionally, the system dynamics should both react slowly enough to demonstrate that process changes are not instantaneous while also reacting quickly enough to limit student boredom when examining dynamic process changes. The four tank system presented in this paper satisfies all objectives for an educational process control experiment.

The experimental four tank pressure system is also a good platform for advanced control courses and research purposes. The system provides and interesting interacting multivariable dynamic process for open-loop and closed-loop experiments. Process nonlinearity is also readily apparent in the open-loop process dynamics. With some tank configurations, the system can exhibit a multivariable right-half plane zero, motivating the examination of input directionality and control limitations [22]. Additionally, for some operating conditions the system can exhibit hybrid dynamic behavior due to sonic flow through the valves.

This paper is organized as follows: a detailed description of the air tank system is first presented. Modeling methods for the system are described, including models based on first principles and empirical methods. Finally, current and future educational uses are described in detail.

2 System Description

The multi-input multi-output (MIMO) experimental system consists of four interconnected air tanks arranged in two parallel interacting systems, each system consisting of two interacting tanks in series. High pressure air (~50 psig) flows into the system through two air-actuated control valves which serve as manipulated variables for the system. Flow

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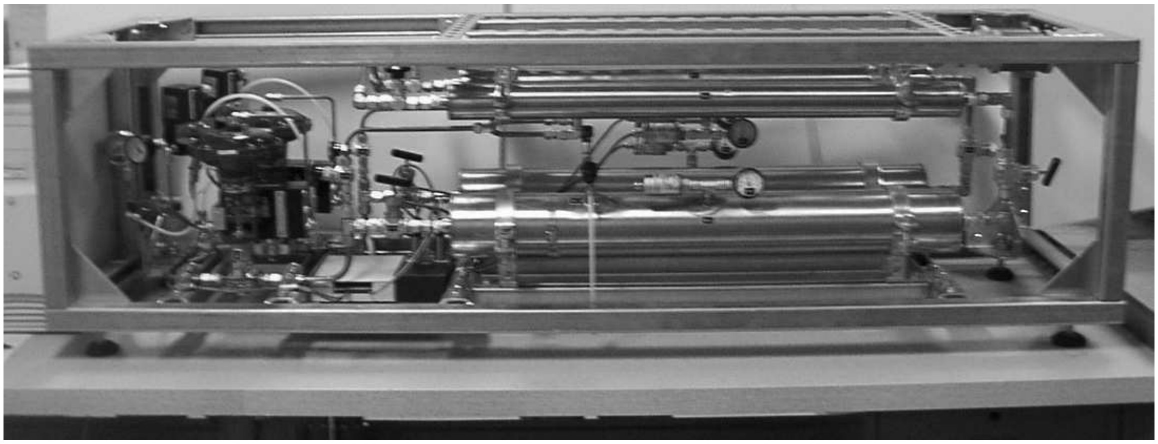

Figure 1: Picture of four tank system.

from control valve 1 flows into tank 1, while flow out of tank 1 fills tank 2 and tank 2 vents to the atmosphere. Additionally, a portion of the flow from control valve 1 can flow into tank 4. Control valve 2 affects tanks 3 and 2. Pressure transducers are used to measure each of the four tank pressures, leading to a total of four possible process outputs. The air flows through the system and then exits to the atmosphere through two outlets. At each outlet, a muffler has been installed to lower the noise level.

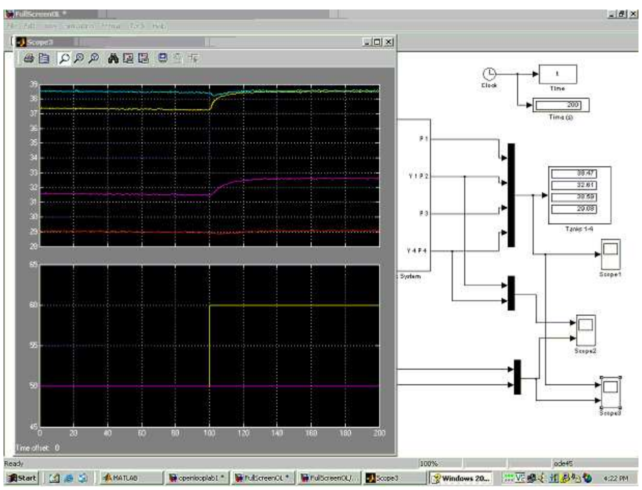

Figure 2: Simulink interface for tank system.

On each side of the system, the upstream tank is a bit larger than the downstream tank. Each of the larger tanks is fitted with a small release valve that vents the tank to the atmosphere. These valves can be used to create a disturbance on the system that might simulate a leak in a given tank. This provides the opportunity to examine disturbance rejection as a possible control objective in addition to reference tracking. In the interest of saving laboratory space, the system is folded over so that the two smaller tanks are placed above the larger ones. A picture of the air tank system is shown in Figure 1. In the basic 2×2 MIMO control configuration, the system measurements are the pressure values of the downstream tanks, P_2 and P_4.

The physical symmetry of the system leads to ability to divide, or classify the system as two "trains" of air flow, each consisting of a control valve, a large tank, and a smaller tank. With this in mind, valves V_{14} and V_{32} allow for the cross-train flow. In some cases, the interacting system will lead to the presence of a adjustable, multivariable right-half plane zero and inverse response. Physically, the cross-train flow produces a fast and direct response in the smaller tanks, while the air flowing through the larger tanks and then into the smaller tanks has a lot slower effect.

The flow of air through the system is driven by pressure gradients. Check valves are not used, so air could flow back upstream, provided that the pressure gradient is in the appropriate direction. Similar liquid systems have had limitations on their flow paths imposed by gravity. All valves not used for control in this system can be establish in a manner such that the system can be operated in any one of many possible configurations. This leads to a flexible dynamic experiment. By opening or closing select valves between the tanks, the system can be quickly transformed from one such configuration to another. One should realize that completely opening valves "joins" two tanks, resulting in one large tank rather than two in series. The possible configurations include: a single tank of numerous possible sizes (depending on the number of tanks utilized), two to four interacting tanks in series, a pair of tanks in parallel, and other setups that would have tanks both in parallel and in series. For example, valves V_{14}, V_{22}, and CV_2 could be completely closed, resulting in a SISO fourth-order system with air flowing through tanks

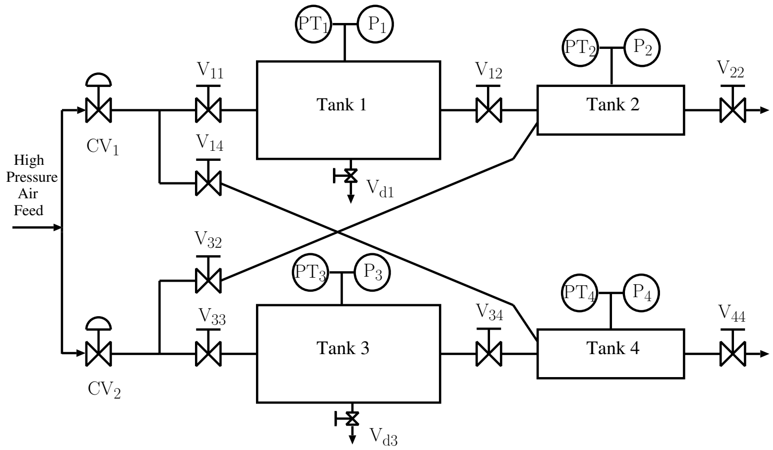

Figure 3: Four tank process flow diagram schematic

1, 2, 3, and 4. Here, CV_1 would be the single input and P_4 would be the single measured process output.

The apparatus is equipped with a National Instruments Data Acquisition system which is interfaced to both MATLAB/Simulink and LabView. Two Badger control valves are used as manipulated variables. Initially, the control valves exhibited substantial hysteresis, making accurate modeling impossible. Valve positioners were required in order for the system to generate reproducible open-loop results. This also helps introduce the students to cascade control and the complexity of real industrial systems.

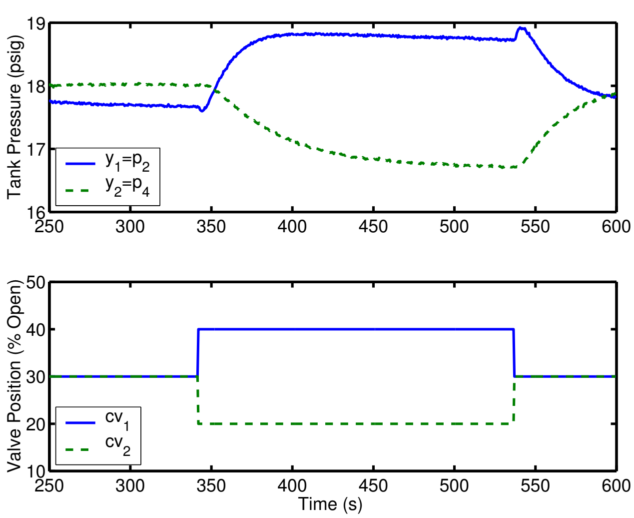

Figure 4: Open-loop plot of dynamic response showing inverse response.

3 System Modeling

3.1 Fundamental Modeling

A high fidelity process model based on fundamental mass balances has been developed for this system. In this model, six process states are used to adequately describe the dynamics of the system. The pressure in each of the four tanks act as states in the model. The two remaining states are not as obvious. The placement of the two valves leading into the two larger tanks cause some resistance to flow, regardless of their position. This, in effect, makes the small sections of entrance tubing between the control valves and these valves act as two additional but very small tanks. The pressure in these extra tanks will acts as the two additional states. No pressure measurements are available for these areas, but the size of these “tanks” and the nature of the system imply that the associated dynamics are extremely fast.

The following mass balances can be established, assuming ideal gas law.

$$
\begin{aligned}
\frac{dN_1}{dt} = \left(\frac{V_1}{RT}\right)\frac{dP_1}{dt} &= f_{V11} - f_{V12} - f_{d1} \\
\frac{dN_2}{dt} &= f_{V12} + f_{V32} - f_{V22} \\
\frac{dN_3}{dt} &= f_{V33} - f_{V34} - f_{d3} \\
\frac{dN_4}{dt} &= f_{V14} + f_{V34} - f_{v44}
\end{aligned}
$$

The two additional tanks needed in order to decouple the pressure across the valves can be described by:

$$\frac{dN_5}{dt} = f_{CV1} - f_{V11} - f_{V14}$$
$$\frac{dN_6}{dt} = f_{CV2} - f_{V33} - f_{V32}$$

From BadgerMeter, Inc. [23] the flow rates through the control valves when the pressure drop across the valve is more than one-half the inlet pressure (P_1) are given by:

$$f_{cvi} = \frac{C_v K \sqrt{\frac{P_1^2}{2}}}{\sqrt{T_1 G_g}}$$

where K is a constant for units, C_v is a flow coefficient, ΔP is the pressure drop across the valve, G_g is the gas specific gravity of the gas, and $T_1$is the absolute upstream temperature.

Otherwise, flow rates for control valves are given by:

$$f_{cvi} = \frac{C_v K \sqrt{P_1 \Delta P}}{\sqrt{T_1 G_g}}$$

Additionally, gas flow rates for Swagelok valves where the outlet pressure (P_2) is more than one half of the inlet pressure are given by [24]:

$$f_{vij} = K C_v P_1 (1 - \frac{2\Delta P}{3P_1}) \sqrt{\frac{\Delta P}{P_1 G_g T_1}}$$

When the outlet pressure is less than one half that of the inlet, the flow rates through the Swagelok valves are given by:

$$f_{vij} = 0.471 K C_v P_1 \sqrt{\frac{1}{G_g T_1}}$$

Specific values for valve coefficients can be found from a nonlinear regression of dynamic data.

3.2 Empirical Modeling

Students in the introductory controls course focus on SISO systems for modeling in control. In these laboratories, student collect open-loop step test data and fit models to that data in the Matlab environment. Students in advanced courses examine multivariable modeling issues. In one lab, the students excite the system using a Pseudo Random Binary Sequence (PRBS) of input changes. Using subspace identification methods in MATLAB [5], the students develop and evaluate the linear state-space dynamic model for the system developed using empirical modeling.

For one system configuration , a LTI state-space model is given as follows:

$$\left[\begin{array}{c|c} A & B \\ \hline C & D \end{array}\right] =$$

$$\begin{array}{cccc|cc}
-0.0033 & -0.0156 & 0.1227 & -0.0566 & 0.0004 & 0.0007 \\
0.0304 & -0.0052 & -0.1056 & -0.1198 & 0.0010 & -0.0007 \\
-0.0786 & 0.0478 & -0.3988 & 0.2319 & 0.0068 & 0.0015 \\
0.0855 & 0.0348 & 0.0204 & -0.3414 & -0.0013 & -0.0062 \\
\hline
3.9568 & -0.6407 & -0.3832 & -0.0431 & 0 & 0 \\
2.0347 & 1.2719 & -0.1719 & 0.2166 & 0 & 0
\end{array}$$

For this system, poles were found to be -0.3756, -0.3052, -0.0235, and -0.0444. Transmission zeros of the system were found to be -79.2 and 0.284 with a corresponding zero input direction for the RHP zero of $u = [-0.6299 \;\; 0.7767]^T$.

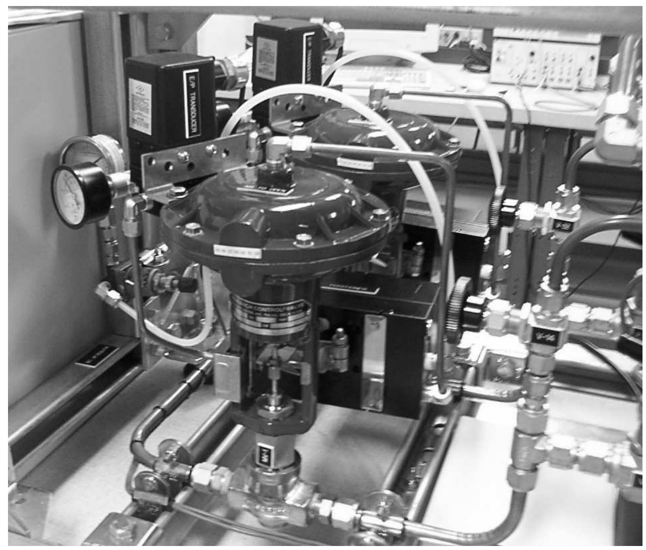

Figure 5: Control valves, including positioner.

Educational Uses

This new experimental system is quite valuable for both educational and research purposes in the area of process control. In the classroom setting, it lends itself well for demonstrations to larger audiences. Alternatively, smaller groups can experiment with the system in a laboratory setting and reap the benefits of learning in a “hands-on” environment. The typical large undergraduate class can be broken into small groups and these groups can then be rotated between the actual pressure tank system and nearby computer labs. In the computer labs, students can utilize the high fidelity model of the system to do simulation work that closely parallels what is to be done experimentally. This way, those entering the computer labs first can prepare for the actual experiment, and those that see the actual system first can later reaffirm what has been done experimentally. These advantages are supported by the fast dynamics of the system and the ease at which the apparatus can be manipulated. In an extended class period, it is possible that numerous groups could be able to get a substantial amount of time working with the actual experimental system.

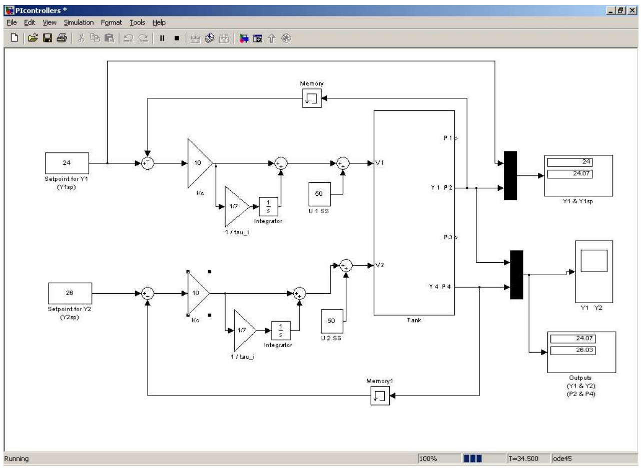

Figure 6: Simulink Interface for Closed-loop control.

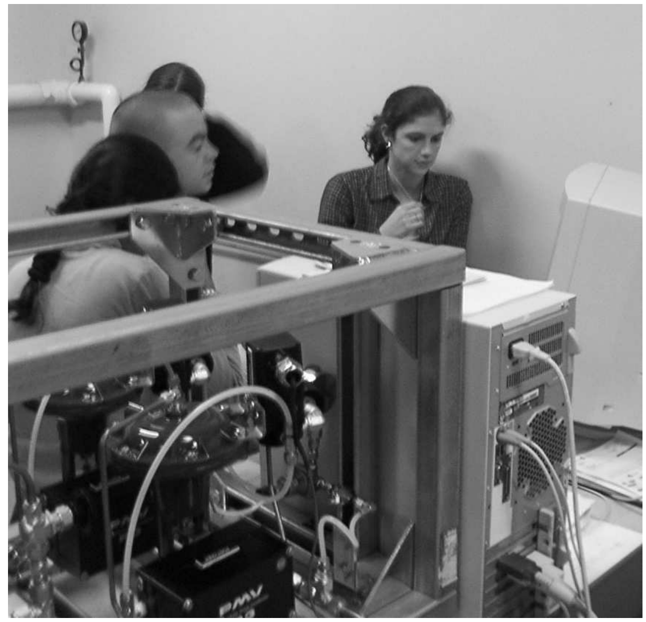

Figure 7: Picture of students performing lab with tank system.

Using this system, many aspects of undergraduate control curriculum can be demonstrated. Open loop modeling can be performed on any of its numerous possible configurations. Closed-loop control methodologies such as Proportional-Integral-Derivative (PID), Internal Model Control (IMC), feedforward control, and cascade control can be implemented. Numerous other fundamental topics including interacting systems, multivariable decoupling, inverse response, closed-loop stability, frequency response analysis, etc. can also be illustrated using the apparatus.

In addition to aiding in the presentation and reinforcement of the undergraduate material, the system can be useful in demonstrating the more advanced undergraduate and graduate level topics. Linear and nonlinear state and parameter estimation routines can be developed for the system. Advanced control strategies can be used, including multivariable IMC, H_∞, and linear Model Predictive Control (MPC). As stated previously, depending upon valve position, this system can also have a multivariable RHP-zero, motivating control performance limitations.

This four-tank system also has potential for use in research in the field of systems engineering. The system can act as a test bed for virtually any new control techniques being developed. More specifically, this system can be modeled as a hybrid system with the model flowrate of air between tanks being dependent on the different pressure drop or flow velocity regimes. This experimental system motivates studies into the area of the control of hybrid systems with switching dynamics.

Overall, student feedback for the experimental four tank system has been positive. Some student comments include:

> “I really like the four tank system because it enables you to apply classroom topics to hands-on applications. The system has many different options which allow you to demonstrate a wide variety of topics... A lot of topics in controls are harder to understand because they are more abstract (you can’t visualize a PI controller like you can visualize a distillation column), but actually applying a PI controller to a real system and watching it work, helps with the understanding.”
>
> “The 4 tank setup provides a lot of advantages due to the flow configurations (series, parallel, cross flow, etc).”
>
> “I like the 4 tank system. It helps me see that real world systems are very different from models of systems.”
>
> “The 4 pressure tank system is fast and flexible. We are able to demonstrate a number of different control strategies with it.”

4 Conclusions

Chemical process control education is often limited by the availability of practical "hands on" educational tools. Few industrially relevant systems are available that offer both reasonable size and cost while providing interesting dynamics with the flexibility to be used in numerous contexts. This paper describes an apparatus with these positive attributes that can provide students the opportunity to actually apply and demonstrate experimentally many of the theoretical concepts that are so fundamental to the subject. A multivariable experimental air tank system has been developed for use as a tool for process control education. Based on four-tank liquid level systems studied previously, this was constructed to be extremely flexible to enable its use for a variety of applications. In addition to its ability to be used to present many aspects of both the undergraduate and graduate level process control curriculum, its hybrid nature poses a interesting research problem for the control of a system that has switching dynamics. A fundamental model was also developed for the system.

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