

**AUTOMATIC LIQUID
LEVEL CONTROLLER
USING A LABVIEW BASED
PC**

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Abstract

A liquid level control system was designed and fabricated to control the level of a liquid in a water tank that had a randomly varying inlet. Control of the water level was accomplished by adjusting a gate valve in the drainpipe located at the bottom of the tank. A solenoid actuator, operated in a continuous mode, controlled the gate valve opening and a pressure sensor provided liquid level feedback to the controller. Input to this system was a random flow disturbance consisting of water entering the top of the tank through three pipes controlled by solenoid valves and programmed to randomly switch on and off. The liquid level control system was implemented with a PC running National Instruments LabView software allowing student interaction with the system. In conclusion, the system using a PC operated successfully and will be used as a teaching tool in a university class on feedback control theory.

I. Background

Automatic control systems have been evolving over the past 150 years[1]. These systems began as simple mechanical feedback devices and have evolved into complex electronic and computer controlled systems. The education of students in control systems is one of the functions of Arizona State University East's College of Technology and Applied Sciences.

This project consists of completing an apparatus that demonstrates the automatic control of water level in a tank that is being randomly filled. Random filling of the tank represents a real life unpredictable disturbance to the system. Automatic control is accomplished with the use of a personal computer operated with LabView software. Automatic control is accomplished by sensing the water level and then controlling the position of a gate valve that releases water from the tank. A manual control is also included so that the benefits of the automatic control can be demonstrated. This physical model will be used as a teaching aid so that the students can interact with and visually see a dynamic control system operating in real time.

Description & Model

The tank system consisted of seven major parts: tank reservoir, gate valve, gate valve actuator, actuator controller, PC system controller, random liquid inlet system, and the bubbler pressure sensor. The tank reservoir was constructed of a 5.5-inch inside diameter vertical Plexiglas tube that is approximately 30 inches high. See Figure 1.1. The operating capacity of the tank was approximately 620 in³ or 2.7 gallons of water. A combination of 1-inch diameter fittings and

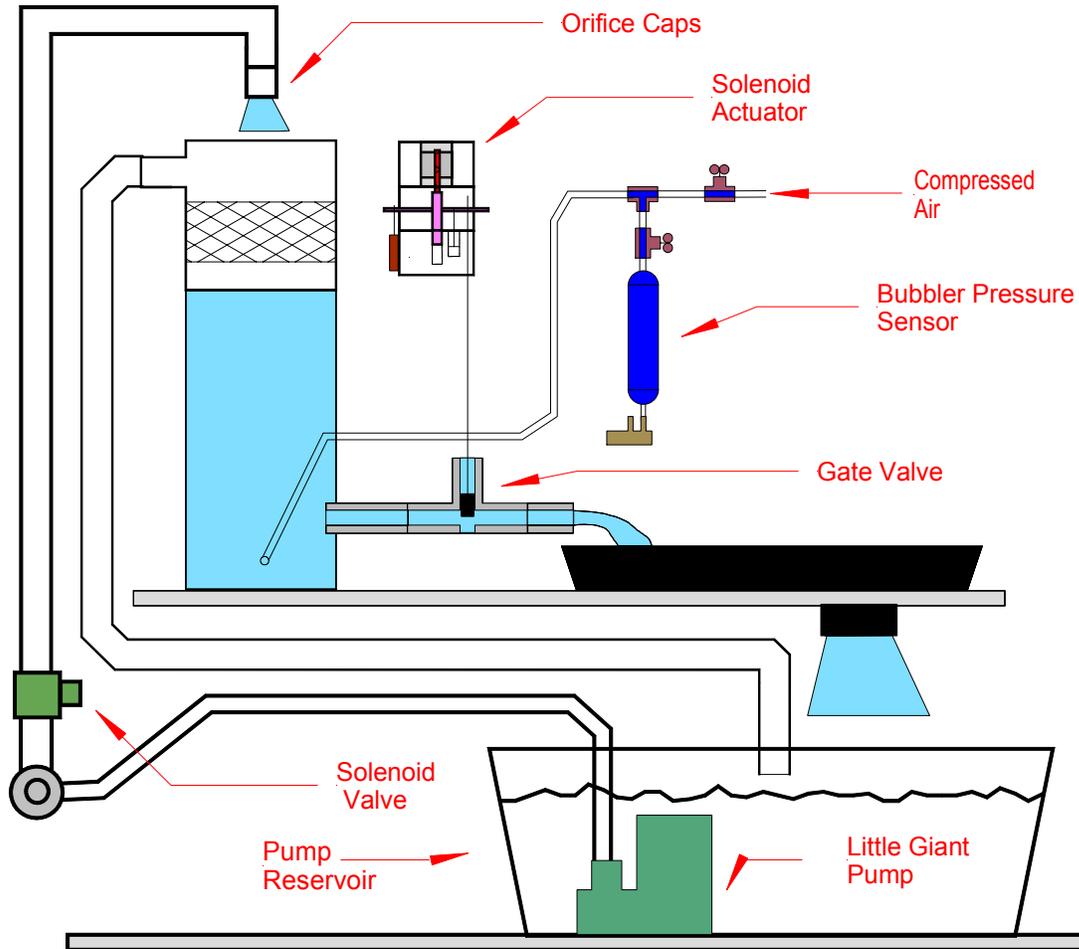


Figure 1.1 Tank System

pipe served as an outlet for the liquid flow and allowed connection of the gate valve attached at the bottom of the tube. A connection for the bubbler hose, located at the bottom of the tank, measured the water pressure or head at the bottom of the tank. Connected to the side of the tube, 5 inches from the top, was a 1-inch overflow hose. Tank overflow is minimized by an overflow opening connected to a hose that re-circulated water into the pump reservoir below the tank. The gate valve controlled the flow of water out of the tank.

Gate Valve

The gate valve, shown in Figure 1.2, is the single control in the system. By adjusting the position of the gate valve, the flow out of it is adjusted allowing the liquid level in the tank to be controlled to a set level. The solenoid actuator controls the vertical position of the valve.

Solenoid Actuator

The actuator is the positioning element for the gate valve. It does this by converting the electrical feedback signal to a linear displacement of its plunger. The actuator sets above the gate valve and is connected to it by a brass rod. The actuator consists of four basic components. See Figure 1.2.

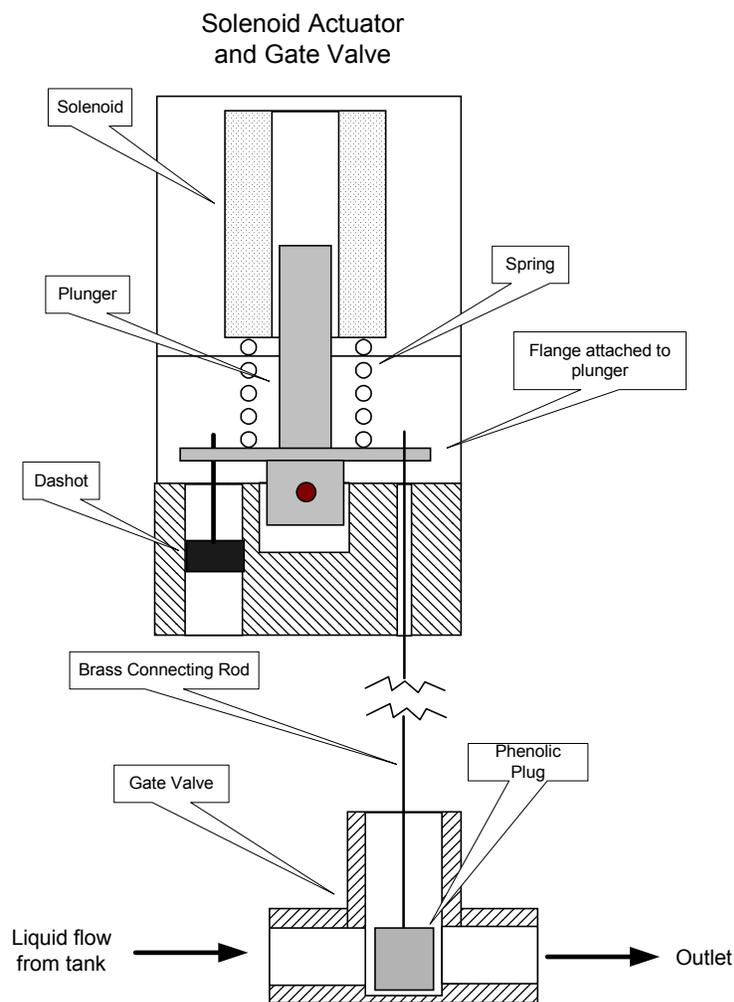


Figure 1.2 Actuator and Gate Valve

The components of the actuator are the DC solenoid, spring, damper and linear feedback potentiometer. The spring and damper have an effect on the dynamics of the solenoid movement. Solenoid plunger position is determined with the linear feedback potentiometer.

Voltage from this potentiometer is compared to the PC controller output at the error summing point in the actuator controller. The magnitude of the error voltage then causes the solenoid displacement, which in turn positions the gate valve.

PC Computer

The PC controller monitors and modifies the feedback signal from the pressure sensor and sends a control signal to the differential amplifier in the actuator controller. It displays the tank liquid level, provides for the selection of three different modes of operation and allows for the input of PID values, liquid level set point and sample time. The controller input is the voltage from the bubbler pressure sensor, which represents the head or water level in the tank. The three modes of controller operation are PID or automatic, on/off and manual control. These three modes allow the operator or student to compare the performance of the system between methods of control. The purpose of the controller is to provide an output that will cause the water level in the tank to approach the set point. This water level will change due to the random water flow into the tank from the random liquid inlet system, which acts as a disturbance to the system.

Random Inlet System

The random liquid inlet system provides a random disturbance to the tank system and causes the water level in the tank to change. This system consists of a PLC or programmable logic controller, pump and pump reservoir, solenoid valves and three vertical inlet pipes that terminate at the top of the tank. See Figure 1.1. The flow rates in the three pipes are: 1.36, 2.83, and 8.56 gal/min. This gives eight combinations of flows that can be programmed into the PLC. An equivalent model of the system was developed.

Equivalent Model

The system can be modeled hydraulically as shown in Figure 1.3. This diagram represents the physical system where q_{IN} is an independent input. Equation (1.1) is a general equation that describes this system. The term q_{TANK} is described by equation (1.2) where C_{TANK} is defined by equation (1.3). Equation (1.4) defines q_{OUT} .

$$q_{IN} = q_{TANK} + q_{OUT}, \quad (1.1)$$

$$q_{TANK} = C_{TANK} \frac{dP_T}{dt} \text{ and} \quad (1.2)$$

$$C = \frac{A}{\rho g} \quad (1.3)$$

Where: A = Cross sectional area of tank
 ρ = Density of liquid
 g = Acceleration of gravity.

$$q_{OUT} = \sqrt{\frac{P_T}{K_{eff}}} \quad (1.4)$$

The complete description of the system is then given by the differential equation (1.5).

$$q_{IN} = C_{TANK} \frac{dP_T}{dt} + \sqrt{\frac{P_T}{K_{eff}}} \quad (1.5)$$

$$C_{TANK} \frac{dP_T}{dT} = q_{IN} - \sqrt{\frac{P_T}{K_{eff}}} \quad (1.6)$$

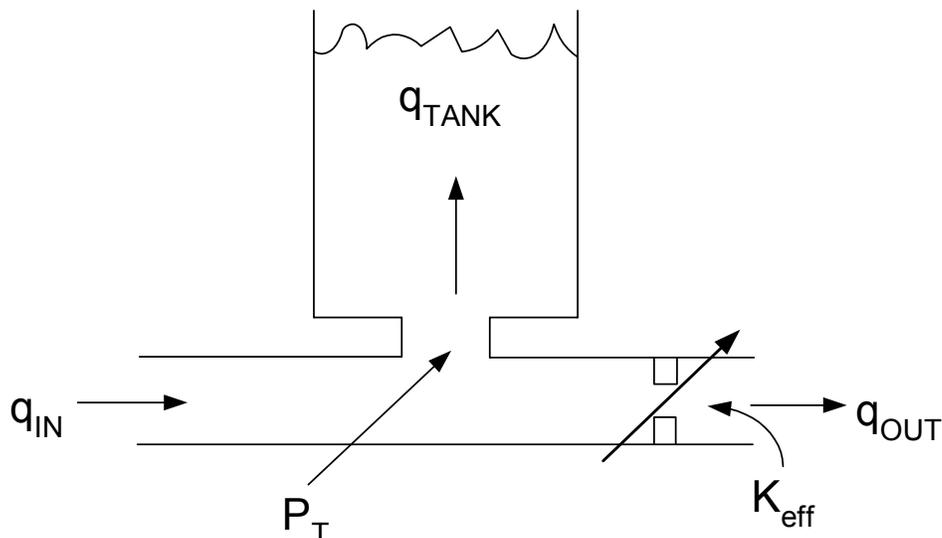


Figure 1.3 Hydraulic Model

As can be seen from equation (1.5), this is a non-linear system. Rearranging equation (1.5) results in equation (1.6). This last equation, (1.6), is used to simulate the tank in the SIMULINK system simulation.

II. Simulations

The tank system was simulated using MATLAB/SIMULINK. The block diagram is shown in Figure 2.3. This diagram shows the closed loop system with negative feedback accomplished by the bubbler pressure sensor. The diagram consists of representations for the computer, PID control, actuator, gate valve, tank, disturbance and the bubbler pressure sensor. The computer output or input to the system is the liquid level set point. Gain, integral and derivative blocks simulate PID control. Simulation of the solenoid actuator is imbedded in a subsystem block. A data look-up table simulates the gate valve. Simulation of the tank is done by solving equation

(1.6), the differential equation that describes its operation. The bubbler pressure sensor is implemented by its transfer function and a gain and offset which represents a pressure to voltage curve fit. This sensor provides liquid level feedback to the computer and closes the feedback loop. The simulation was first run using proportional gain only.

Simulation Results

The block diagram shown in Figure 2.3 was run in SIMULINK using proportional gain only. It was run at a set point of 15 inches and a gain of 10. The results of this simulation are shown in Figure 2.1. It can be observed from this figure that the fill rate was 1.24 gal/min corresponding to the actual system fill rate, which was the liquid inflow minus the leak in the gate valve.

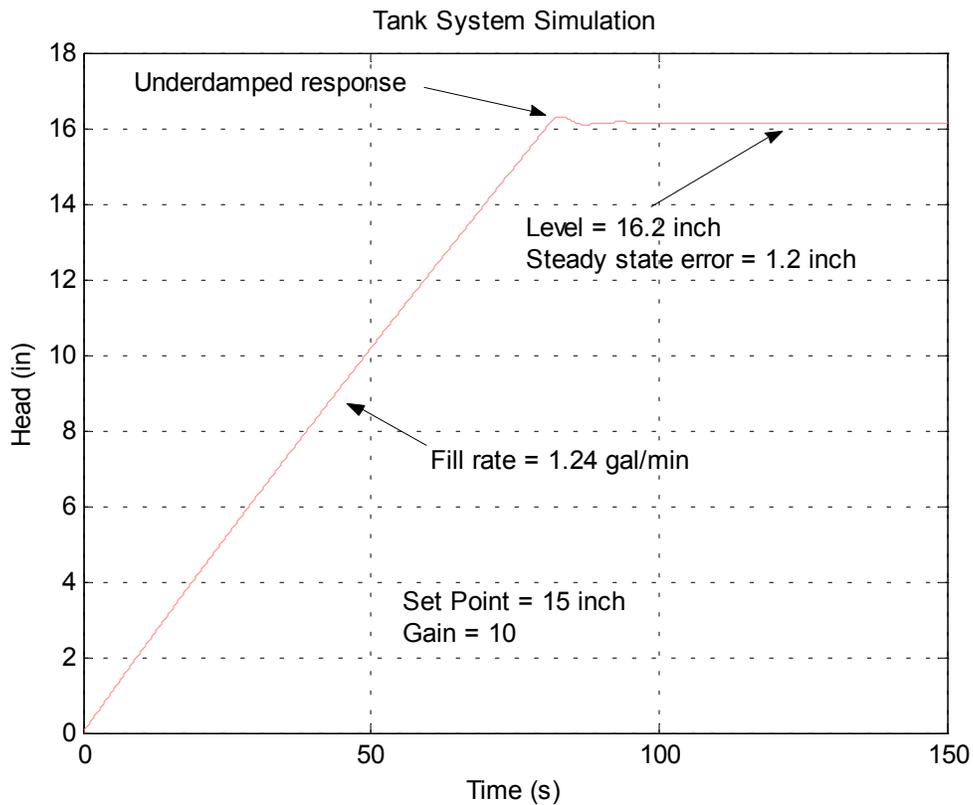


Figure 2.1: Tank Simulation

Also, the response when the set point was reached was under damped and the steady state error was 1.2 inches. The steady state error was large because the gain was low. A higher gain would reduce this error but could also cause the system to become unstable. PID control was used to modify the response of these characteristics.

PID Control

The PID function controls the behavior of the tank system. Three different gains interact and are adjusted to optimize the operation of the tank, usually so that the response to a change in the level set point or the random input is not excessively under damped. Also, the proportional and integral components can be adjusted to reduce the steady state error. Equation (2.1) describes this function. P is the proportional gain, $1/T_i$ is the integral gain and T_d is the derivative gain. This equation is called the non-interacting, parallel, ideal or ISA form and is one of several different forms that can describe the PID function [2].

$$PIDOutput = P \left[e(t) + \frac{1}{T_i} \int e(t) dt + T_d \frac{de}{dt} \right] \quad (2.1)$$

This equation was implemented as shown in Figure 2.2. The integral function was implemented by the Laplace transform $1/s$ and the derivative operation by the transform s . The P, $1/T_i$ and T_d coefficients are adjusted to produce the desired system response. The PID modified error voltage is the input to the actuator subsystem. The tank system with PID control is shown in Figure 2.3.

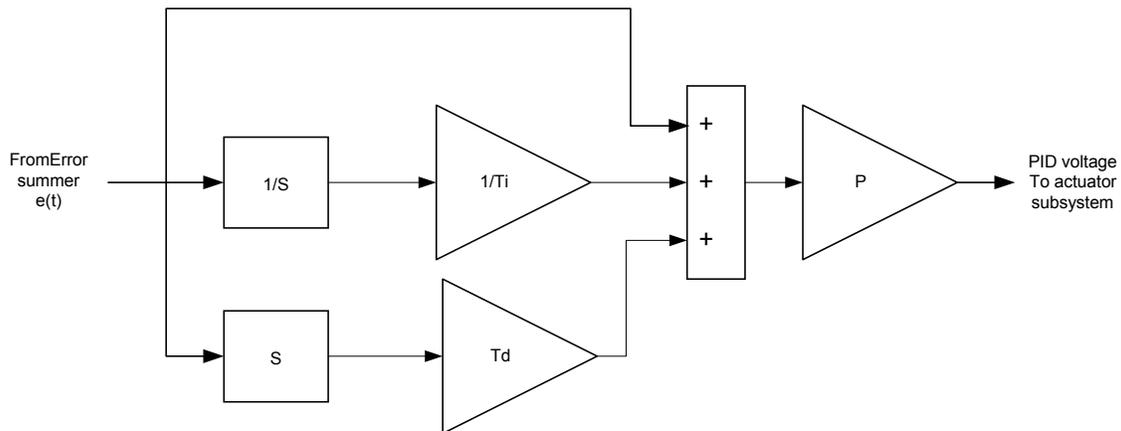


Figure 2.2 Simulation of PID Control

III. LABVIEW PROGRAM

The tank system was controlled with a desktop personal computer. This computer was equipped with a National Instruments, NI, PCI data acquisition card and the LabView graphical programming language. The data acquisition card used was the NI PCI-6024E. This combination of hardware and software made it easy to focus on building the programs necessary to control the tank system.

The computer controls the tank system through connections to the data acquisition card. There was one input to the card and one output from the card. The A/D input was from the voltage output of the pressure sensor, which represents the head in the tank. This input ranges from 1.5 to 9 volts. The D/A output from the card was the input to the actuator-summing node, which controls the position of the solenoid plunger and therefore the gate valve. This output ranges from 3 to 8 volts. Three programs were built to control the tank system and are described next.

Three different LabView programs were constructed to demonstrate three different types or methods of control. These methods were manual, on/off and automatic. The manual control used a joystick attached to the computer to control the gate valve opening. The voltage output from the pressure sensor was used to indicate the liquid level on a front panel chart. The on/off control simply fully opens the gate valve or closes it around some liquid level set point and uses the pressure sensor feedback to determine that point. Full automatic control continuously adjusts the gate valve opening to control the set point using feedback from the system. With manual control, the joystick operator becomes the feedback by observing the level of liquid in the tank to control to the set point. On/off control switches the valve open or closed around the set point using hysteresis. Automatic control continuously adjusts the gate valve to control the liquid level to a change in the set point or to a change in the liquid input to the system. This method gives the most accurate control of the set point. Automatic control that incorporates PID has the advantage of changing the response of the system or how it behaves to changes in the set point or disturbance. Feedback for both the on/off and automatic control comes from the pressure sensor. Figure 3.1 is the front panel for the automatic control program. These three programs allow the student to compare each method and observe its strengths and weaknesses.

The PID calculation was performed in the automatic LabView program as described in equation (3.1).

$$PID_{OUTPUT} = K_P e(t) + K_I \int e(t)dt + K_D d \frac{d e(t)}{dt} \quad (3.1)$$

The coefficients of equation (3.1) were adjusted to optimize the response of the system to changes in the liquid input or set point. This was accomplished using a process called tuning[3]. To do this, equation (3.1) was arranged so that it conformed to one of the three basic forms for the PID algorithm [2]. The form used is equation (2.1) from section II, repeated on the next page as equation (3.2). This form was changed to equation (3.3).

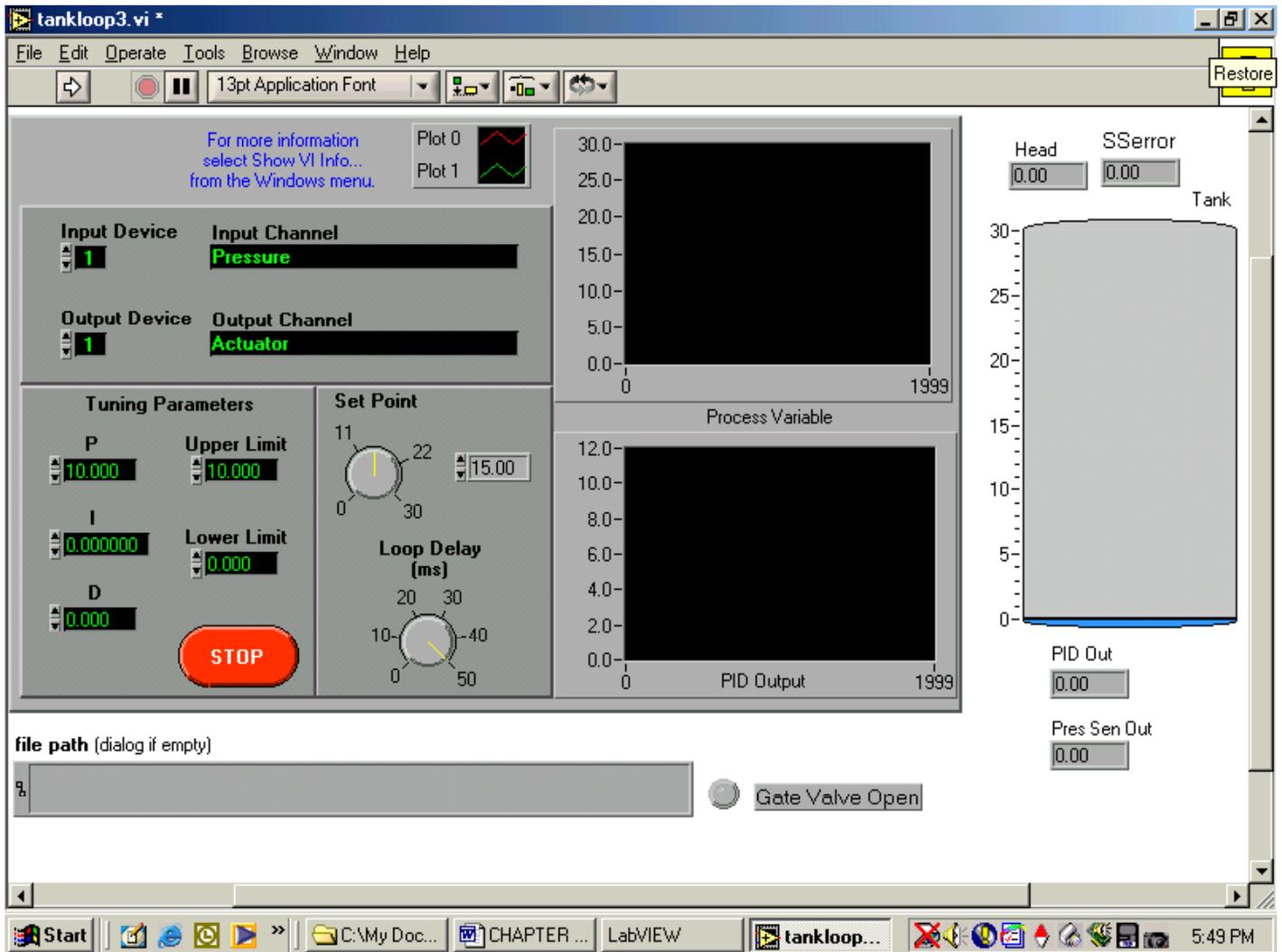


Figure 3.1: Automatic Program Front Panel

$$P\left[e(t) + \frac{1}{T_i} \int e(t) dt + T_d \frac{de(t)}{dt}\right] \quad (3.2)$$

$$P e(t) + \frac{P}{T_i} \int e(t) dt + P T_d \frac{de(t)}{dt} \quad (3.3)$$

The coefficients for equations (3.1) and (3.3) were set equal to one another. The results were equations (3.4), (3.5) and (3.6).

$$K_p = P \quad (3.4)$$

$$K_i = \frac{P}{T_i} \quad (3.5)$$

$$K_D = P T_d \quad (3.6)$$

Finally, the coefficients for equation (2.1), P , T_i and T_d , were determined through the tuning process described by St. Clair [3] and then converted by equations (3.4), (3.5) and (3.6) to fit the

form required by the LabView Program. The derived equation for the computer PID output was used to tune the tank system for optimum response to system changes.

IV. Results

This section will explore the results of the tank simulation and the performance of the physical tank system. The values for the PID coefficients were determined by the Ziegler-Nichols tuning method for the model simulation and then applied to the physical system. Tuning is the term used to describe the process of optimizing the performance of automatic feedback systems [4].

Ziegler-Nichols Tuning

In 1942, J.B. Ziegler and N.B. Nichols proposed a set of rules for tuning automatic controllers [3]. These rules consisted of increasing the gain of a closed loop feedback system until the output response goes into sustained oscillation. The gain at which this oscillation occurs is called the ultimate gain, P_U , and the period of the oscillation is called the ultimate period, T_U . These values are combined with the coefficients in Table 4.1 to generate a set of PID values that produce an acceptable stable system. This technique was applied to the tank simulation.

Gain, P	Integral Time, T_I	Derivative Time, T_D
$0.6 P_U$	$0.5 T_U$	$0.125 T_U$

Table 4.1: Ziegler-Nichols Coefficients

Applying the Ziegler-Nichols method to the simulation model resulted in PID values of $P=24$, $T_i=5.5$ and $T_d=0.688$. A plot of the response using these values is shown in Figure 4.1.

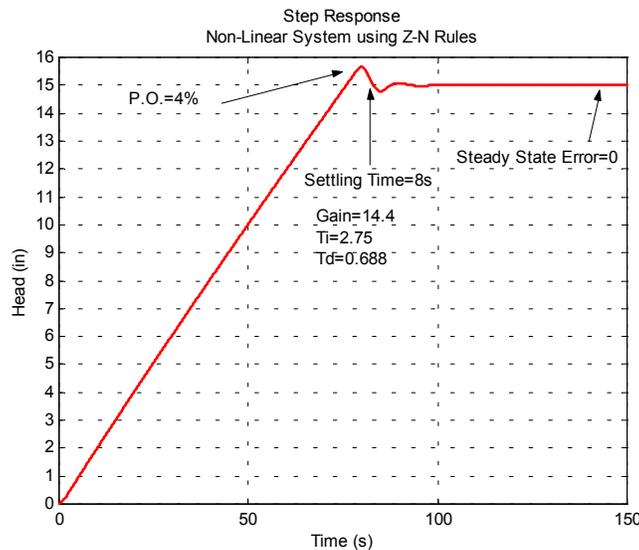


Figure 4.1: Model Response Using PID Coefficients Obtained using the Ziegler-Nichols Tuning Rules

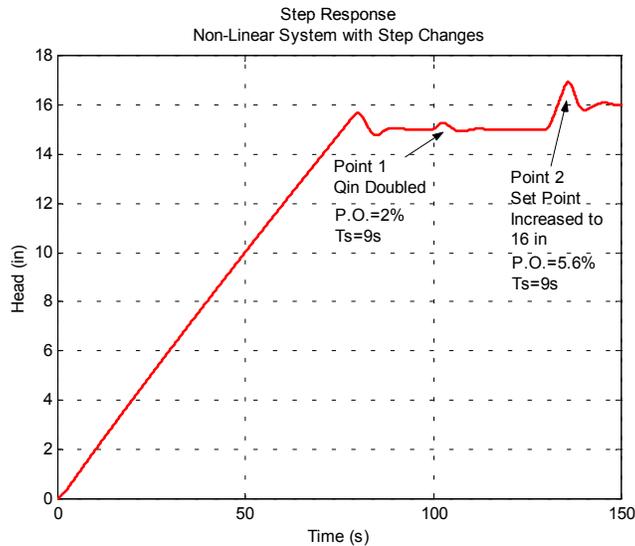


Figure 4.2: Model Response to Changes in Input Flow (Point 1) and Set Point (Point 2)

It should be noted from Figure 4.1 that the steady state error is zero. This is because of the integrator in the controller. Another simulation was run with changes in both the set point and fill rate. This is shown in Figure 4.2. It can be seen in this figure that doubling the input flow, Point 1, causes a small response and the level quickly returns to the set point. A change in the set point, Point 2, causes a larger response but again quickly adjusts to the level of the new set point. These PID values were applied to the physical tank system.

Physical Tank System

Several response parameters were considered. The first was steady state error, the difference between the set point value and the actual level in the tank. This was approximately 5% with a proportional gain of 25 in the initial test. This was at a level set point of 15 inches. Any gain value above this caused the system to become unstable and the gate valve to oscillate. Other response characteristics considered were settling time and percent overshoot. These values were 90 seconds and 7% respectively. Tuning was used to alter or improve these parameters.

The Ziegler-Nichols PID values found for the simulation model were applied to the physical tank system. First, a plot of the system operating with proportional gain only was made for comparison. This is shown in Figure 4.3. It should be noted that the gain is ten and the integral and derivative gains, K_I and K_D , in the LabView software have been set to zero.

The percent overshoot and steady state error were 1.8% and 11% respectively. Again, it can be noted that with proportional gain only, there will be some steady state error. The gain can be increased to reduce this error but the system will become unstable before it decreases to zero. The model PID values were applied to the system.

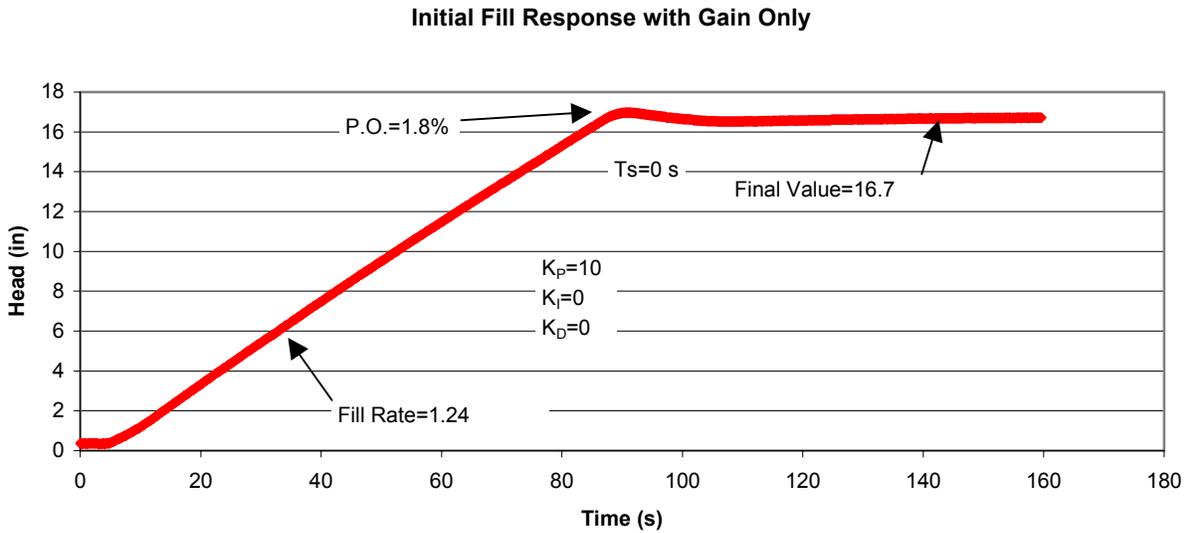


Figure 4.3: Tank with Proportional Control

The PID values found for the simulation were converted to the form required by the LabView program using equations (3.4), (3.5) and (3.6). These converted values were $K_p=24$, $K_i=4.36$, and $K_d=16.51$. The response plot with these PID values is shown in Figure 4.4. The start of this plot was done with the system stabilized at a head set point of 10 inches. The set point was then increased to 15 inches. Overshoot was approximately 4% with a settling time of 5 seconds and an average steady state error of zero. Inlet flow was then increased to 4.2 gal/min. Overshoot was approximately 2% with a settling time of 3 seconds and an average steady state error of zero.

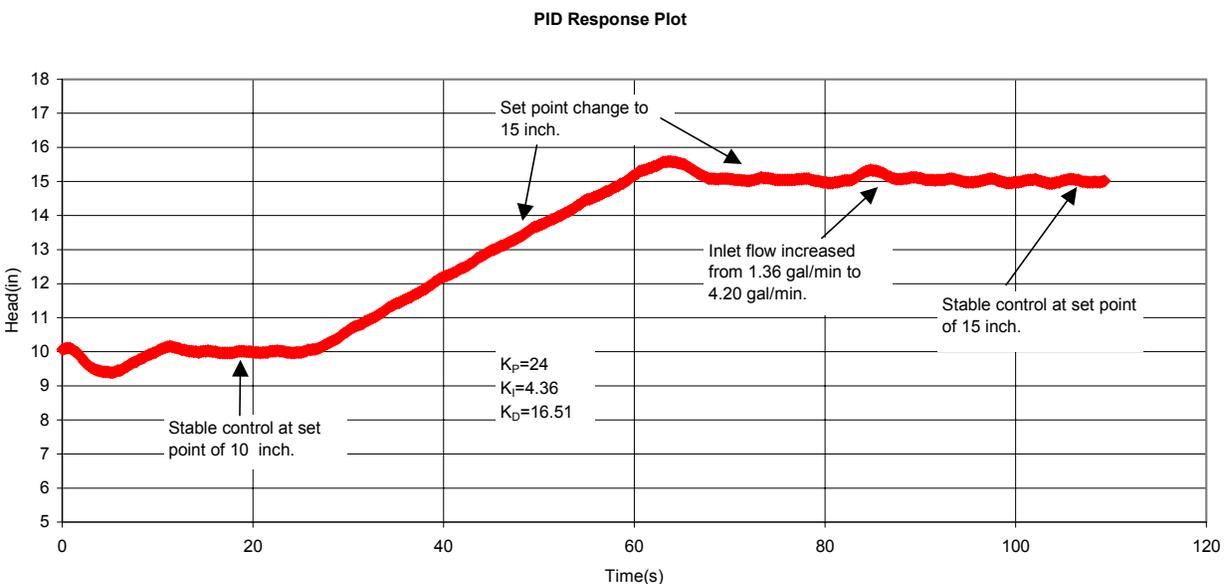


Figure 4.4 Tank with PID Control

The small variations in the steady state level are thought to be caused by sticktion in the solenoid actuator assembly (Coulomb friction).

All three programs were tested for accuracy and precision by operating each and then calculating their average and percent standard deviation. Each program was run for several minutes and the data recorded. Table 4.2 lists the results. All three methods control well, but automatic control has the least variation, 0.3%. Bang-Bang control has the most variation but controlled close to the set point. Its main disadvantage may be that it would cause excessive wear on the actuator and gate valve, as they must constantly move from one extreme position to the other. Manual control can also be accurate but requires a steady hand and especially constant attention.

	Automatic	Bang-Bang	Manual
Average=	15	14.8	15
SS _{ERROR} =	0%	-1%	0%
Stdev=	0.04	0.3	0.2
%Stdev=	0.30%	1.80%	1.20%
Min=	14.9	14.4	14.6
Max=	15.1	15.3	15.4

Table 4.2: Statistical Results

V. Conclusion

A tank system was constructed as a classroom model to demonstrate three different methods for controlling the liquid level in the tank. These methods were automatic, Bang-Bang and manual control. Automatic control was accomplished by utilizing negative feedback from the pressure sensor. Bang-Bang or on and off control switched the gate valve between full open and full closed around the level set point using hysteresis. Manual control was implemented by using a joystick to control the gate valve while the joystick operator monitored the liquid level visually. Attached to the tank are a pump, associated plumbing and valves that provide either three separate flow rates, or a random sequence of all three, to represent a random disturbance to the system. The random sequence was accomplished through the use of a programmable logic controller that controlled the valves. The system was built at ASU East. Because the system was built internally it allowed for easy maintenance and modification of both the system and software. In addition, thousands of dollars were saved compared to the purchase of a commercial model.

All three programs or control methods successfully controlled the liquid level. As was expected, automatic control using a PID controller preformed with the least error and variation, although the other two techniques performed adequately. Simulations of the system were carried out

using MATLAB/SIMULINK. Tuning techniques performed on the Simulink model were successful and the results were successfully applied to the physical system.

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Bibliography

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