Process Control Virtual Laboratory Manual

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THE PROCESS CONTROL VIRTUAL LABORATORY MANUAL

ARMFIELD PROCESS CONTROL RIG

The Process Control Virtual Laboratory (PCVL) is educational software programmed in LabVIEW for demonstrating control systems concepts via manipulating a simulated model of a physical process. The software has been developed at Loughborough University to complement hands-on laboratory activities that are performed on Armfield PCT40 experimental rig. The PCVL provides a virtual model of Armfield PCT40 tank filling process plus additional control and regulation capacities. The PCVL can be generally used by control systems students and lecturers as a virtual lab activity; furthermore those who have access to Armfield PCT40 rig might find the PCVL a valuable add to the physical rig. The next section provides a brief description of the Armfield PCT40 experimental rig and then is followed by sections of the PCVL.

The Armfield PCT40 system, shown in Figure A, provides a way of teaching a range of process control techniques. Level, flow, pressure and temperature control loops can be demonstrated with the system.

The Armfield plant itself comprises a variable volume process tank, a hot water tank with electric heater and indirect heating/cooling coil, a hot water pump, two non-dedicated pumps, three on/off solenoid valves and a proportioning valve. The instrumentation includes temperature sensors, two differential water pressure sensors and a mechanical level sensor (float switch). The additional module PCT41 extends the rig functionality by adding a process vessel package that comes with a heating/cooling coil and a stirrer and with conductivity and pH probes. The platform is multifunctional and all the parameters (inputs/outputs), e.g. the pump speeds, the valve positions and the heater power can be

Figure A: The Armfield PCT40 rig with PCT41 module. The unit can be used for demonstrating many process control exercises such as level control, heat transfer, pressure control etc.
controlled from a PC through a USB connection with the unit. The system is supplied with a dynamic link library (DLL) driver for connectivity with LabVIEW, Matlab or C++. Hence, specific software systems can be programmed for educational purposes. The main utilised parts of the rig to compose a level control experiment are the variable process tank, of the non-dedicated pumps and the proportional valve; see Figure 1. The PCVL is designed based on this arrangement.

**THE PCVL INTERFACE**

The main interface of the PCVL is shown in Figure B. The main interface is designed with the vision of giving access to four main experimental interfaces: level tank control, pressure control, temperature and flow control, and a project work interface. Currently, the tank level control experiment interface is active while the rest are to be developed in the future. The tank level control experiment is a typical process control engineering used exemplar in undergraduate control systems courses. A special and detailed laboratory manual for the tank level control experiment is provided below. The lab can be conducted virtual via the PCVL and proximally with the Armfield PCT40 experimental rig. The aim of the lab is to familiarise first or second year engineering students with basic concepts of instrumentation and control concepts.

![Picture of the Armfield rig](image1)

![Temperature and Flow Control Experiment](image2)

![Tank Level Control Experiment](image3)

![Pressure Control Experiment](image4)

![Project Work](image5)

Figure B: The Graphical User Interface of the Process Control Virtual Laboratory.
1. INTRODUCTION

The laboratory is an introduction to the dynamic behaviour of modular equipment and the operation of a feedback controller. The principle aim is understand the role and operation of the main components in a feedback loop: (i) sensor, (ii) actuator (input valve) and (iii) controller.

The plant to be controlled is a liquid tank with a peristaltic pump in the outlet stream. To an acceptable approximation, the liquid flow from the tank is independent of the liquid level in the tank. The flow of liquid entering the tank is independent of the tank’s liquid level; as a consequence, the tank acts as an integrator, integrating the difference between the flow in and the flow out. Control action is needed to stabilize the liquid level by making one of the flows dependent on the liquid level. Figure 1 shows a schematic diagram of the tank process.

![Simplified Diagram of a Surge Tank Control System](image)

2. OBJECTIVES

A. Week 1
A1. Calibrate the level sensor.
A2. Calibrate the inflow PSV valve. Study the installed characteristics of the valve.
A3. Study if there is a hysteresis in the control valve and sensor.

B. Week 2
B1. Understand the dynamic behaviour of the system
B2. Evaluate manual control.
B3. Evaluate the tuning of a PID control via manual and automatic tuning.
B4. Evaluate the effect of positive or negative feedback on the closed-loop system
3. PREPARATION

1. Download the “Process Control Virtual Laboratory” and familiarize yourself with the software and procedure.
2. Go to Appendix B and familiarize yourself with the rig and its software.

4. EXPERIMENTAL PROCEDURE

I. Sensor Calibration

Introduction
A level sensor is an essential element in all chemical plants. The signal obtained from the device is usually a standard electric signal (e.g. 0-5 V). This value needs to be correlated with the real level in the tank to obtain the desired information. This process is called calibration. For appropriate level control and monitoring the characteristics of the level sensor needs to be determined. The level sensor is a linear device, which may exhibit hysteresis in the output. The output (voltage) can be related to the input (level) by the equation:

\[ \text{Level}(\text{mm}) = K_s \cdot \text{Voltage}(V) + Z_s \]  

(1)

Where \( K_s \) is called the sensor’s Gain (defined as changed in the Output over change in the input) and \( Z_s \) is the Zero of the instrument.

![Image of Level Sensor Calibration](image.png)

Figure 2. Reading the Level Value and the Corresponding Sensor Voltage
Calibration Procedure

1. First, determine the range of operation of the sensor's input variable (i.e. the liquid level) and output variable (i.e. the voltage sent to the controller). This can be done in with the controller in manual mode and using the following procedure:

   a. Fill the tank until it reaches the maximum level “100%” by closing any outflows (i.e. SOL2, SOL3, and Pump A) and setting PSV to a relevant value, i.e. 50. Once the tank is full (or just at the saturation edge of the level sensor), read the “Level (%)” value from the rig software, the tank real level from the scale placed on the tank, and read the corresponding voltage signal from the software as shown in Figure 2. Record the data on your notebook.

   **Important Note:** In the physical process, the sensor voltage may SATURATE before reaching the maximum level of the tank. In this case, record the level value at which the sensor voltage saturates and also record the maximum voltage value. Consider not exceeding these values for your calibration, and the consequent experimental procedures.

   b. Empty the tank fully by opening SOL2, SOL3 and/or Pump A (PSV is set to zero). Once the tank is empty, read the “Level (mm)” value from the software, the tank reading from the scale placed on the tank, and read the corresponding voltage signal “Level (V)” as shown in Figure 2. Record the data in your notebook.

2. Starting from the liquid level zero, fill the tank to the level 10 (%) and read the “Level (mm)” value from the rig software, and read the corresponding voltage signal “Level (V)” of the level sensor. Record the data on your notebook. Repeat the same for levels (20 %, 30 %, 40 %, etc) until you reach the maximum level. You can manipulate the level by changing the input flow rate through the PSV valve, the outflow Pump A, and valves SOL2, and SOL3.

3. Repeat the same steps but reversely from the maximum level until 0 (i.e. 100 %, 90%, etc).

4. To assess the extent of hysteresis calibrate the sensor using strictly increasing liquid levels and then reverse the process using falling liquid levels. Use for calibration the voltage values reading from the software and the corresponding level values (%).

5. Plot the calibration curve and determine the gain and zero of the instrument by fitting a line to the experimental data. Perform separate fittings of the increasing and deceeding data, as well as using all data points, and comment on the results obtained.
II. Calibration and Characteristics of the Proportioning Solenoid Valve PSV

Introduction
A control valve is a device which allows changing flow resistance, through a changing external input signal. A control valve changes the flow of a fluid by altering the valve's flow resistance.

A solenoid valve is an electromechanical valve for use with liquid or gas controlled processes by running or stopping an electrical current through a solenoid, which is a coil of wire, thus changing the state of the valve. Solenoid valves are the most frequently used control elements in fluidics. Their tasks are to shut off, release, dose, distribute or mix fluids. They are found in many application areas. Solenoids offer fast and safe switching, high reliability, long service life, good medium compatibility of the materials used, low control power and compact design.

Experimental procedure for the solenoid valve calibration

To eliminate the effect of the changing water level in the tank on the input flow rate, open SOL2 and SOL3, and the manual valve at the bottom of the tank.

1. Determine the range of operation of the valve’s output variable (the flow rate of water) that corresponds to the valve’s input variable (the signal from the controller, i.e. 0-100%).

2. SET and RECORD the input variable to the valve at a number of points (approximately 10) and MEASURE and RECORD the output variable (flow rate of water through the valve) through reading the “Flow” measurement on the rig software. After each change wait a few seconds until the readings stabilize.

3. To assess the extent of hysteresis perform the calibration process by strictly increasing the signal to the valve and then reverse the process using strictly decreasing signals.

4. Plot the valve characteristics (flow rate versus signal to valve in %) and comment on the results.
PART 2 - WEEK 2

III. Experimental procedure for the study of feedback control loop.

The objectives of the exercises are to gain familiarity with feedback control, to appreciate the importance of automatic control and controller tuning, and to gain qualitative appreciation of the effect of each term in a three-term controller on the control performance.

Manual Control

Set PSV to 50% and close SOL2 and SOL3.

1. With the controller in AUTO mode define a set point (e.g. 50%) and wait until the system stabilizes (Set the controller parameters e.g. to $K_c=3$, $T_i=0.7$, $T_d=0$).
2. Turn the control mode to MANUAL, and change the setpoint (e.g. to 60%).
3. Try to bring the water level to the new set point through manipulating Pump A.
4. Repeat the procedure at a different setpoint.
5. Record the data and analyse the observations. Remember that you can record the measurements in excel file, by pressing the Send to Excel button after the experiment. You can also record and paste in a Word document the figure plotted by the software by right clicking on the figure window and selecting “Export Simplified Image” and then paste into a word document (as described in the Appendix). Your data will also be saved in a file automatically. You can change the file name before you start a particular part of the experiment to divide your data files in smaller files. In your report discuss how easy/difficult is to maintain the setpoint? This is one of the simplest processes, where you only had to control one single parameter! What is the control error in the case of manual control, i.e. what is the maximum deviation from the setpoint?
6. In the final report present the figures showing the outcome of manual control together with your comments.

Automatic control with heuristic tuning

The most common controller used in the process industries is the so-called three term controller, or PID (proportional-integral-derivative) control. The controller calculates the error between the measured signal and the desired value and changes to manipulated value (valve position) so that the error is decreased. The amount of change in the manipulated value is a function of the error. This function in the case of PID control has three main components.
The control performance depends strongly on the three parameters of the three term controller:

- Proportional Gain ($K_p$)
- Integral Time ($\tau_i$)
- Derivative Time ($\tau_d$)
Procedure

1. Set the control mode to AUTO, and wait until the system stabilizes at the desired setpoint value (e.g. 40%).

2. Test the performance of the default control parameters by changing the three controller parameters and comparing how the controller performs in the case of different setpoint changes. Observe how large the overshoot is, how fast the system reaches the new setpoint or whether there is a steady state error, and if there is how large it is. Analyse the form and speed (oscillations, noise level, etc.) of the control action together with the variation of the water level.

3. In the Controller pane of the software, modify one of the three “PID parameters” at a time. Test first the P only control by setting Ti=0 and Td=0 and changing Kc. Test different gains (minimum 3 different values, e.g. 0.1, 5, 20).

4. Next, fix Kc to 3 and vary Ti (e.g. 0.01, 0.1, 1, 10) and change the set point every time you vary Ti (Start from set point 30% and increase 10% each time you change Ti) and observe the system behaviour. What do you notice when Ti is introduced? Can you find a value of Ti that bring the system to the desired set point without oscillation?

5. Next, fix Kc to 3 and Ti to 0.7 and vary Td (e.g. 0.1, 1, 10). Comment on the impact of Td on the overshoot and oscillations. Notice the Pump A behaviour after the system stabilizes on the set point. How does it differ from the case of the PI controller?

6. Record the used control parameters and plot the results in your report. Analyse the effect of each term on the control performance.

Important Note: The suggested values are just heuristic, you are encouraged to test your own values and validate your own hypothesis.

Evaluation of regulatory control (Disturbances rejection)

1. With a fixed set of controller parameters (i.e. Kc=3, Ti=0.7, Td=0) test the control performance for different input flow rates (Input Disturbances). When the system reaches a stable level, increase or decreases the input flow (through altering PSV) within the physical limits of the controllable system. This will act as a disturbance in the system and the controller will increases or decreases the Pump A speed accordingly to bring back the level to its setpoint value. Determine what the maximum input flow rate is, for which the controller is not able to stabilize the system anymore. Explain in your report what the reason is and give an explanation how the maximum input flow rate, for which the controller can stabilize the system, relates to the output flow rate from the tank.
2. Next try **output disturbances** through switching on SOL2 and SOL3 when the system reach stability and observe the system behaviour, will the system become stable again?

**Effect of controller sign on system stability**

1. With the best set of controller parameters change the sign of the controller gain $K_c$.
2. Give a set point change and observe and RECORD the controller action and system’s behaviour.

**Automatic tuning**

The systematic determination of the controller parameters is called tuning procedure. There are numerous ways to determine the controller parameters based on the criteria considered. The software includes an “Automatic Tuning Wizard” which can help to determine the set of tuning parameters.

1. With the control mode on AUTO, wait until the system stabilizes at the desired level.
2. Start the “Automatic Tuning Wizard” from the Controller pane of the window by pressing the “Autotune” button. Follow carefully the procedure. Make sure that you wait enough when the procedure requires to gather information from the system. During the procedure observe that the Autotuning wizard will introduce relay signals in the system to understand its dynamic behaviour. The information is used to determine the control parameters. At the end of the procedure the new parameters will automatically be saved into the current PID parameters tag in the controller pane and will be used in the system. Test the control performance by changing the setpoint and/or introducing disturbance by changing the input flowrate. Record the controller parameters and the resulted figures.
3. Repeat the autotuning wizard and tests for different controller types. Tune P, PI and PID control structures with Fast, Slow and Normal action. It is not necessary to tune all combinations. Use your observations from the previous experiments to choose the best controller structure (e.g. PID and PI) and determine the parameters for the fast and slow response. Justify in the report why a particular type of controller (P, PID, PI was used).
APPENDIX A

Laboratory Report
A group report is required. The body of the report should be no more than 20 pages. You should include key figures, tables and calculations in the main body of the report but you may attach any extra data and peripheral information to appendices, which may be of any size.

Structure and Guidelines for the report:
Summary
Provide a paragraph of the main purpose of the report and a summary of the most important findings.
Table of contents
Introduction (0.5-1 page)
A short introduction related to the importance of understanding process dynamics and control should be provided. The introduction must contain several references. Use appropriate reference style.
Theory (2-5 pages)
Explain in a few sentences the theoretical background related to: (1) how the sensor works, (2) calibration, (3) how the control valve works, (4) PID control. This part should be your own description not copied from the lab manual, with references demonstrating your readings on the topics.
Experimental Procedure (2-4 pages)
Provide a brief summary of the procedure. It is not necessary to copy the procedure from the manual. You should describe briefly the methodology. A proper P&ID of the experimental rig must be provided using standard symbols for instrumentation. It is important that all instruments and elements of your rig are shown in the P&ID.
Results and Discussions (6-10 pages)
Show all results requested in the lab manual. This should contain as a minimum: results from level calibration, analysis of hysteresis, valve calibration, analysis of hysteresis, calculation of the relative control valve resistance, figures and discussion on manual control, results on heuristic tuning, automatic tuning and effect of controller signs. Always compare/contrast and analyse your results, do not only show figures with simple plots. Make sure that the controller tuning parameters are indicated for different parts of the figure and you correlate the dynamic response in your discussion with the changes in the parameters. Main figures should be inserted in the text (always number figures and use figure caption).
Conclusions (0.5 page)
A brief statement with the main results and conclusion of the report.
References
Use proper referencing style and make sure all references are cited in the report.
Appendices
Marking guidelines

Organization
Are the report contents structured?
Is a table of contents present?
Are the pages numbered?
Is a summary present?
Are equations numbered?

P&ID
Is the P&ID correct?
Are the manual valves labelled?
Are the symbols correct?

Figures & Graphs
Are the figures and graphs clear?
Is the precision of the data reflected in the graphs?
Is proper analysis and discussion provided?
Are the figures numbered, captions used and referenced properly in the text?

Summary
Does the summary reflect the experimental observations?
Are the numerical values of the principal parameters tabulated?
APPENDIX B

Armfield Test Rig and Software
To start the software, go to Start → Process Control Virtual Laboratory → PCVL. Once the GUI appears, choose “Level Control Experiment”; the interface will appear as below.
Saving your data

Making sure that your data is saved is your responsibility. The software offers several ways to record your data.
1. By pressing the “Send to Excel” button, you can send the data from the memory of the software to an Excel workbook. This option works in the opposite way as the Save button. By pressing the button data stored in the memory from the moment you started the software until the moment the button was pressed will be sent to Excel.

2. You can save your data in separate file, e.g. different file names for different tasks, by inserting new name as shown in the figure below. When you press on the (OK) button, the folder that contains your data will be opened.

3. You can also copy paste snapshots of the plot into your report. However to perform the data analysis you need the values saved with method 1 or 2 above. For the qualitative analysis part or for the appendix it is acceptable however to use the snapshots. This can be obtained by right clicking on the figure widow and selecting “Export Simplified Image…”, then paste it in Word, as shown in the figure below.