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A Process Control Platform for Education in the Virtual Factory Laboratory System

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Abstract: This paper describes an experimental platform which is useful for graduate and undergraduate education in control engineering. It contains a six-tank liquid level regulation system and a pilot distillation column, which can be used as stand-alone apparatus. Some extensions of the apparatus are made to increase the function of the platform. The compositions of distillate can be estimated by adding soft sensors to the distillation column. Integrating with liquid level regulation system makes the inlet and outlet flow of the distillation column controllable which provides a realistic engineering experimental environment. It is possible to describe the impacts of unloading from upstream and charging to downstream as in process industry. The platform has been used for graduate courses such as system identification, soft sensor designing and advanced control system.

1. INTRODUCTION

It has long been recognized that the laboratory experiment is a good way to help interpreting theory and industrial situation. It greatly enhances the flexibility of laboratory education, reinforces the concepts presented in a lecture practical and provides student to demonstrate in a mostly realistic laboratory, and establishes a direct link between the scientific researches and the needs of the local industry.

At present most universities rely more on simulation as a tool for teaching. As laboratory scale models of industrial processes cost much, hardware-in-the-loop simulation environment and the related software are designed to implement control engineering course and for system testing (Grega, 1996; Li et al., 2004; Sanvido et al., 2002). With the combination of laboratory devices and software, a real-time digital control environment with magnetic levitation device is developed for modelling with emphasis on neural network feedback control (Stephen et al., 2004). Liquid level regulation system using water tanks with different connections as control object is also studied (Edward et al., 2000; Roberto et al., 2002). But, they are mostly virtual or partially virtual limited for single purpose. As “graduate control” can refer to a course more than just feedback control and include modelling, identification and other topics (Thomas et al., 2006), these laboratory platforms cannot meet the needs for both graduate and undergraduate education.

The platform presented in this paper provides an environment with physical equipments to accommodate a variety of tests for graduate and undergraduate students. It is the PCS (process control system) part of the virtual factory laboratory system which is composed of several other parts including a simulation platform, an information integration system and a MES (manufacturing execution system). They are integrated in a proper way (Feng et al., 2005). The simulation platform is based on a dynamic simulation of a crude oil distillation process to support the MES for further application such as operations performance evaluation, decision, measuring, planning and scheduling (Fang et al., 2006). The PCS platform is the physical under-layer of the system composing a six-tank liquid level regulation system and distillation column which could be used for testing identification algorithms and model-based control algorithms. The most novel idea is that some extensions are made to the existing equipment enabling graduate students to better utilize the platform. Liquid level regulation system and distillation column are linked together so that the integrated process forms a snapshot of operation unit and storage tanks. Moreover, these links make some variables of the distillation column measurable and controllable. The system can expose students to process details which are often neglected in computer simulation, and provides students an engineering experimental environment to face realistic industrial problems. Examples are presented to illustrate the utility of the integrated PCS platform.

2. COMPONENTS OF THE PLATFORM

The process control system platform contains the following core parts: (1) liquid level regulation system, (2) distribution control system, (3) distillation column, (4) real-time database. They are integrated into one platform as shown in Fig. 1. Additional details of each block are discussed in this chapter.

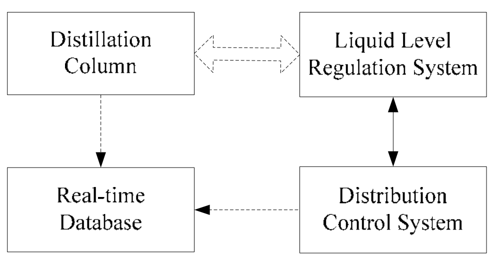

Fig. 1. Process control system platform

2.1 Liquid level regulation system

Liquid level regulation system is a classical installation in control labs. As shown in Fig. 2, the system is composed of six quadrate tanks under which differential pressure sensors are installed to measure the liquid levels. Six flow meters are installed in pipes. Several switch-valves are used to divide the flow so that liquid is channelled to aim tank. Students can choose to design different experiments by adjusting the valve (Feng et al., 2005).

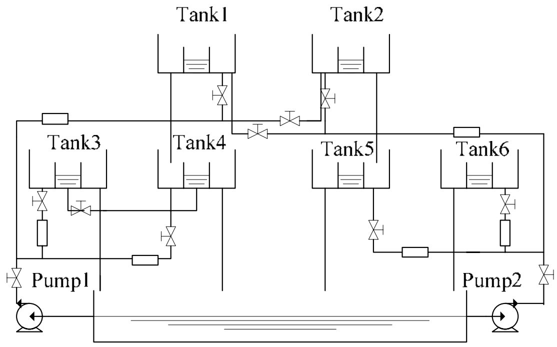

Fig. 2. Liquid level regulation system

2.2 Distribution Control System

DCS is short for distribution control system. It has an operator workstation utilizing personal computer connecting the plant apparatus. Information of the liquid level regulation system can be derived and passed over the link to workstation which is the window into the process including graphic representation of the process with control function. DCS also has the ability to network with real-time database.

2.3 Distillation column

UOP3CC is a continuous binary distillation column made by Armfield Corporation in UK. It has eight plates. The total pressure drop across the column is indicated on a U-tube manometer. Temperatures within the system are monitored by fourteen thermocouple sensors located at the strategic positions. Depending on the setting of the reflux times, condensate is directed by the reflux control valve which is three-way solenoid operated either back to the column or to the collecting vessel. Software is supplied with the column allowing data logging using computer. And signal output port which is voltage output for each of the sensor is provided for further extension.

2.4 Real-time database

Real-time database provides open database interface, realizes the function of access to distillation column. At the same time, it gathers, archives, and processes operational data across DCS simultaneously through OPC (OLE for Process Control) interface. Therefore real-time database makes it possible to integrate the distillation column and liquid level regulation system. Meanwhile it enables personnel to manipulate real-time data as well as make better use of historical data.

3. APPLICATION OF THE STAND-ALONE APPRATUS

3.1 Identification of liquid level regulation system

To introducing theory at a practical level, liquid level regulation system is widely used. It provides a “real engineering fact” experimental environment for system identification of dynamic multivariable process model. The liquid level regulation system is possible to form different models by adjusting the corresponding valves, all identification models of our apparatus are listed in Table 1.

Table 1. Identification models

Experiment	Linearity	Model order	Equipments needed
SISO open loop closed-loop	Linear or nonlinear	1~3	Pump, valve, tank1,4
MIMO open loop uncoupling	Linear or nonlinear	1~2	Pump, valve, tank1,2,4,5
MIMO open loop coupling	Linear or nonlinear	1~2	Pump, valve, tank1,2,4,5
MIMO closed-loop coupling	Linear or nonlinear	1~2	Pump, valve, tank1,2,4,5
Self-designed experiment	Nonlinear	1~3	Pump, valve, Tank1~6,

For instance, MIMO open loop coupling experimental model has two inputs and two outputs. The output variables, levels of tank 4 and tank 5, are influenced by two pump opening values respectively, thus, MIMO open loop coupling model is constructed. If pipes from pumps connect with tank 1 and tank 2, levels of tank 4 and tank 5 are not directly influenced by pump opening values, and tank1, tank4, tank2, tank5 constitute second-order objects. The apparatus can also support self-designed experiment, so students can use any number of tanks, pumps and valves by needs to construct models.

Here we take the SISO second-order model as example. Except for tank 1 and tank 4, other tanks are not used. We choose opening of pump 1 to be input and the level of tank 4 to be output. Liquid pumped to tank 1 directly flows to tank 4 and forms a level. Using certain functional boards in tanks non-linearity could be modified and the model shows to be a linear one. The block diagram of the model is shown in Fig. 3.

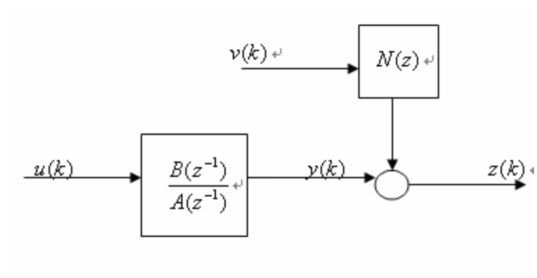

Fig. 3. Block diagram of SISO second-order model

According to the model, structure variables are known prior and parameters needs to estimate. During the experiment, real-time database gathers the required data from DCS which is passed to MATLAB through OPC (OLE for Process Control) interface. Using the data the parameters can be calculated by different identification algorithms, then the transfer function is obtained. In the example, least squares method is used (Ljung, 1986).

3.2 SISO temperature control of distillation column

Distillation column is one of the most common processes in refinery and petrochemical industries. It is possible to configure two different control loops to indicate the single loop feedback control with Armfield software. One of the loops is reboiler power control from a bottom tray temperature and the other is reflux control from the top tray temperature. The loops can be configured individually or simultaneously. It is an introductory education for undergraduate students to learn about basic definition of control system, such as command input, actuating signal, open-loop control, closed-loop control and so on. By doing the experiment, it demonstrates a typical application of a PC for PID process control. Students could observe the response of the process when there is a change of set point or a disturbance. It is helpful to learn about how to adjust the settings of the controller for optimum control effect.

4. EXTENSION OF DISTILLITION COLUMN

Though UOP3CC is sufficient as a chemical unit, it is limited for graduate students major in control. For example, the concentrations of products must be analyzed off-line, there are only PID controllers in the column, sensors to measure the inlet and outlet flow rates are absents. So some extensions should be made to the distillation column to meet the needs of systems engineering education and research. Soft sensor and virtual advanced controller are developed to get the target of ensuring better control performance. The method of adding supervision to flow rate by connecting liquid level regulation system and distillation column as an integrated process is outlined.

4.1 Soft sensor

In industry, main composition concentration in top product and bottom by-product is very important because it directly affects the quality and yield of product. Soft sensor is needed when there is a limitation of measurement technology, or the setting would bring the instability or there exists large time delay using on-line sensor (Zhu et al., 2004). It is based on the relationship between the known variables and the parameters to measure. Because the existing distillation column has no such measurement, the concentration of distillate has to be sampled and analyzed off-line which leads to inevitable disturbance and time delay. Soft sensors using artificial neural network combined characteristics of ethylene production has been successfully applied to distillation column in plant (Li et al., 2004). Students are encouraged to apply different algorithms to measure ethane concentrations in products to understand the soft sensor. For example, the ethane concentration of top product is mainly affected by top column temperature (T1) and feed concentration (FC), the result of soft sensor is shown in Table 2.

Table 2. Ethane concentration of top product

T1(℃)\FC(%)	0.05	0.1	0.2
85	27%	35%	43%
88	29%	40%	49%
90	32%	49%	55%
93	33%	39%	58%
95	37%	32%	64%

By doing this exercise, students comprehend the distillation column according to vapour-liquid equilibrium, overall material balance and energy balance. And black-box method such as neutral networks and extended Kalman filter method could be used for soft sensor. Then the concentration of the product can be estimated based on the method. At the same time, it is possible for graduate students to compare the performance of different estimation algorithms or develop new methods.

4.2 Selective controller

When the quality of product is ensured, it is easier to control the entire column. Because the controller attached to UOP3CC is fixed and only PID parameters can be tuned to control the distillation column, virtual advanced controller is designed in MATLAB/SIMULINK software package. Students can design or improve advanced control algorithms based on mathematical model then implement them to the physical process to get a better effect (Roberto et al., 2002).

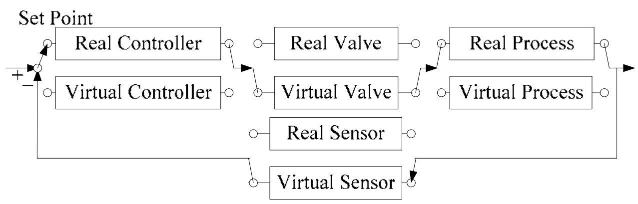

Fig. 4. Architecture of the multiple channel system

In UOP3CC, all signals are included in the input/output channels. Using A/D and D/A conversion, the signals can be transmitted to SIMULINK toolbox and it is possible to do experiments using advanced control schemes rather than PID control. Further, combined with a first-principle model build in SIMULINK, a hardware-in-the-loop simulation based on the existing distillation column is conducted. The proposed system provides a free switch without disturbance between real and virtual settings as shown in Fig.4. Students may first apply their completed advanced control algorithms to virtual model, after testing and debugging, these schemes could be executed in the real process.

In Fig. 4, real process is the distillation column, and the virtual part is a dynamic model with the same structure parameters of the real one. Real sensors are fixed on distillation column such as thermocouple sensors, and virtual ones are integrated in the column model. The real controller is PLC (Programmable logic controller), the virtual one is a control algorithm programmed in MATLAB. The controlled variables can be temperature, or distillation composition. The multiple channel system ensures every part of the system can be substituted by the corresponding one. Different combinations of switches achieve demanded aims.

This extended function exposes users to be familiar with MATLAB, SIMULINK, and relevant toolboxes. It easily permits graduate and undergraduate students to accommodate advanced control learning.

4.3 Integrated process

Input flow and output flow rates are key inferential parameters in distillation column control because they affect the characteristics of column and cause different product purity. But in the pilot column the feed is pumped from the feed tank by a peristaltic type pump incorporating a length of rubber tubing without any sensors. And the top product passes directly through a decanter to the colleting vessel with a valve in the bottom. So it is necessary to improve the distillation column.

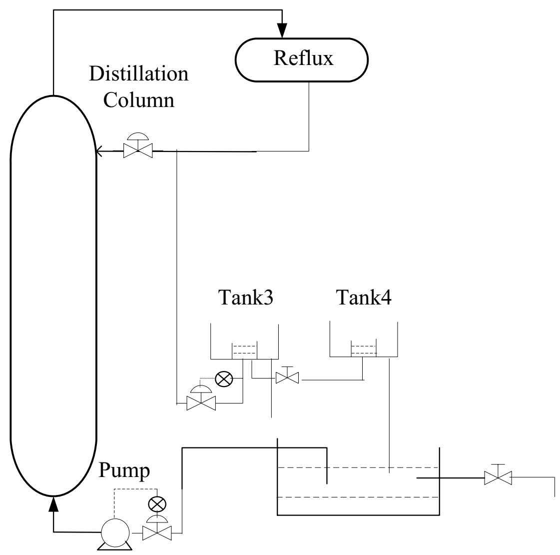

Fig. 5. Architecture of the connected system

It is destructive when adding hardware to distillation column because pierces for installing sensors will break the sealed column body made of glass. Meanwhile it takes time to integrate the related signals. Then a connection between distillation column and the liquid tanks is built so that sensors are shared. One feed entrance reserved for batch operation of the distillation column is linked to the electronic pump at the base of the liquid level regulation system instead of breaking the column to set a sensor. The flow rate to column is able to be measured and controlled by DCS. Then a flexible pipe from the top product receiver valve is attached to the inlet of a water tank. The flow rate can be calculated in computer through the changing level of the water tank which can be measured by the differential pressure sensor. Signals generated by liquid tanks and distillation column can be transmitted to the same computer. The architecture is shown in Fig. 5.

This special architecture can be seen as partial atmospheric and vacuum distillation unit of a refinery. For example, the inlet is built up to represent source of a material movement, the amount of crude must be restricted to satisfy the process capacity. The column can be seen as a simplified crude distillation unit, and stock tanker area is substituted by the liquid tanks. The connected physical devices are able to run as the real process of the factory.

In refinery and petrochemical industries, effective control of distillation columns leads to better product quality, production flexibility and lower energy consumption. So students can implement their own methods to achieve the goal as well as understand the real process. As there are many disturbances in the column, for example, inlet flow, boiling setting and pressure changes, a cascade control strategy can be used to achieve better disturbance rejections. In this loop, the controlled variable is the first plate temperature (T1) of the column. In the inner loop, inlet flow to the column is supposed to be at the set point and the disturbance is from the water pump. In the outer loop, the disturbance is the changing boiler power. Sensor 1 is located in the water tube of tanks and sensor 2 is a thermal couple. The system performs better than single feedback control under this strategy (Fig. 6).

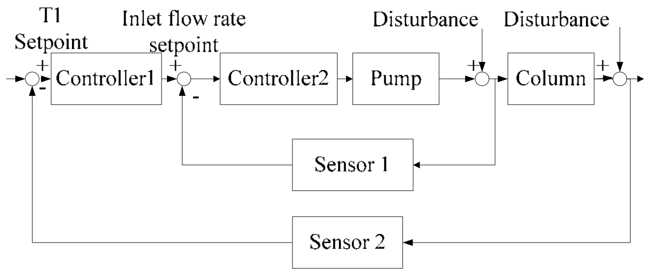

Fig. 6. Cascade control

However, a time delay exists in the outer loop of the cascade control because the temperature of the distillation can not drop immediately when cold feed is pumped in. In this case, a Smith predictor scheme can be used for a suitable set point response. Furthermore, a PI-PD structure, which is proved to give better performance, can be used in the outer loop to improve the performance of the system even better (Kaya, 2001). This can be implemented referring to 4.2. As there was no such physical instrument in laboratory before, students usually simulated the process and saw the response in trend graph. They may just know the block diagram but not interpret the discipline. After they design the algorithm and apply it to the real process, they understand the theory better through the phenomena. And it is easy for them to learn about the operations in refinery.

At present, most advanced controllers are based on the model of a process including the Smith predictor scheme. Referring to 4.2, a system model is essential for availability of the designed control strategy, so identification of integrated process is needed. These practices are offered for graduate students. The model should capture the main characteristic of the process. The inputs of the process are reflux and inlet flow rates, the outputs are top product and bottom product temperature. The data for identification is saved in real-time database. It is generated by the connected apparatus where reflux is used to control the top temperature and inlet flow rate is used to control the bottom temperature. The sample time is 5 seconds. In total 1000 data points the first 700 samples will be used for identification and the second 300 samples will be used for model validation (Zhu, 1999). Graduate students are encouraged to introduce different system identification approaches to capture precise model, for example, least squares method or maximum likelihood algorithm. Toolbox of MATLAB can also used to predict the parameters of the model by a high order ARX. The fit error of the model is about 20%. Once students gain the right parameters, the interface provided by the DCS can allow them free switch between model and physical column as shown in Fig.7. This helps them to develop control strategies before applying to the real system avoiding energy consumption.

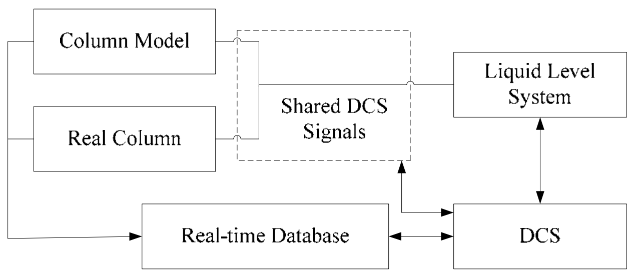

Fig. 7. The integrated experiment system

By doing a series of experiments in the PCS platform, graduate students are capable of using various software tools and developing programming skills. They are knowledgeable about applying advanced control technology into real process. They are able to translate complex problems into mathematical models and convert data into information. The experience helps them to adapt new environment in industry or accelerate them enrolling into the further research.

As mentioned in 2.1 and 2.3, the liquid level regulation system was designed and constructed by the colleges in the laboratory, and the distillation column was purchased from Armfield. By linking the two separate systems, it provides a relatively new experimental environment for students to put the theory learned into practice. The integrating method may be helpful to other process control laboratories solving the problem of balance between the desirable objective of teaching and cost of equipment.

5. CONCLUSIONS

In this paper, the development and applications of process control platform for graduate and undergraduate education are presented. The platform provides an environment for implementing control and identification algorithms as well as soft sensor designing. The data of all signals can be observed and saved within real-time database for subsequent use, such as off-line system identification and data mining. The combination of liquid level regulation system and distillation column allows students to focus on the task of understanding the real process in industry, thus perform more complicated approach to satisfy certain requirements. Currently the platform is being utilized in the teaching of system identification course and advanced control engineering course in the Department of Control Science and Engineering in Zhejiang University.

AKNOLEDGMENTS

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