AUTOMATION AND CONTROL OF CHEMICAL AND PETROCHEMICAL PLANTS

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Contents

1. Introduction

The chemical and petrochemical industries produce a wide variety of products that are essential for modern industrialized societies. Chemicals are the building blocks for products that meet fundamental needs for food, health, and consumer products. Chemicals are also essential to wide range of industries such as pharmaceuticals, automobiles, textiles, furniture, paint, paper, electronics, agriculture, construction, and appliances. The fuels produced by petrochemical plants play a vital role in meeting our and energy and transportation requirements. Although there are legitimate concerns about the environmental and safety issues associated with these industries, it is very difficult to imagine how industrialized societies could sustain a high standard of living without these products.

The operation of modern industrial plants would not be feasible without automation and process control. This paper provides an overview of process control objectives and methodology in the chemical and petrochemical industries. But first, basic background material for these industries will be presented.

2. The Chemical and Petrochemical Industries

The chemical and petrochemical industries are a key component of the world economy, as will be illustrated by a few statistics. The world production of chemicals for 1999 has been estimated at €1370 billion (or $1592 billion U.S. dollars.). Table 1 indicates that about 85% of this world chemical production is divided equally among three regions: Western Europe, the United States, and Japan.

[Table 1 here]

In the United States, the chemical industry is the third largest manufacturing sector, representing approximately 10% of all manufacturing. More than 70,000 different products are registered in the United States. Table 2 lists the 10 chemicals that were produced in the largest quantities in 1999.

[Table 2 here]

Petroleum products have been the world's major energy sources for decades. The projections in Table 3 indicate that this trend is expected to continue.

[Table 3 here]

The refining of crude oil produces a wide range of products that are used for energy and chemical feed stocks, as shown in Table 4.

[Table 4 here]

Chemical and petrochemical plants vary from small facilities that produce single products to complex manufacturing facilities that produce a wide range of products and occupy several square miles. Large manufacturing plants are located worldwide and require huge capital resources to build. Historically, plant sites have been situated close to raw materials and/or product distribution centers.

Chemicals produced in small quantities (e.g., less that 1000 tons per year) are typically manufactured in *batch processes*. A batch process consists of a series of separate activities that are performed in a sequential manner. In a typical batch process, the raw materials and additives such as catalysts are initially placed in a closed container (i.e., a process *vessel*). Then the process is initiated (e.g., by heating the vessel or turning on a stirring device) and a series of steps (a *recipe*) are followed. Finally, the product is removed from the vessel and transferred to another vessel for further processing or storage. Batch processes are also used when a high degree of flexibility is required to accommodate frequent changes in product grades and marketplace demands. Many pharmaceuticals, polymers, paints, and specialty chemicals are produced in batch processes. Cooking food on a stove or in an oven is a familiar example of a batch process.

Chemical and petrochemicals that are manufactured in large quantities are produced in *continuous processes*. In a continuous process, a *feed stream* of raw materials is continuously added to the process unit and a product stream is continuously withdrawn. Large continuous processes tend to be operated "around the clock", i.e., 24 hours per day, 7 days a week, with shutdowns for planned maintenance occurring once or twice each year. Continuous processes are attractive candidates for the application of advanced process control and optimization techniques because a small reduction in the unit cost of product results in huge annual savings due to the large production rate. This paper will emphasize control of continuous processes due to their economic importance and their heavy reliance on control and automation.

During the past 20 years, the chemical and petrochemical industries have faced a number of critical business and technical challenges:

1. Increased global competition;
2. Enormous fluctuations in raw material, energy, and chemical product prices;
3. Increased customer demand for high quality products;
4. More stringent environmental and safety regulations.

Due to uncertain economic conditions and the large capital costs associated with the manufacturing plants, it is not feasible to redesign the plant to meet each new challenge. Consequently, there has been increased emphasis on operating plants more efficiently and economically. For the past 20 years, advanced automation, process control, and on-line optimization have played key roles in improving plant performance.

3. Historical Perspective

Early industrial plants were controlled manually using only a few measurements. The modern era began in the 1920s and 1930s when automatic feedback control was used to control individual process variables such as liquid levels, pressures, flow rates, and temperatures. The introduction of automation was particularly beneficial when the control actions were tedious and repetitious. The first generation of instrumentation and controllers consisted of pneumatic (i.e., air powered) devices. At first only proportional feedback control was used; later, integral and derivative control modes were added. In these early applications, the controllers and recorders were mounted locally, close to the equipment being controlled. But in the 1930's, it became possible to transmit pneumatic signals, such as measurements and controller outputs, over long distances. This breakthrough allowed control equipment to be consolidated in central control rooms with subsequent reductions in manpower.

Electronic instruments and controllers entered the marketplace during the 1950s. They were analog devices that had continuous input and output signals. The first digital computer control applications were reported in the late 1950s and early 1960s. A typical first generation computer control system had 32KB of memory, one MB of disk storage, and required one second to retrieve stored information from the disk. These early computers were mainly used for data acquisition and as information systems. Automatic chemical composition analyzers that could be used "on line" as part of a feedback control system, were introduced during the 1960s. Simple digital devices, called *programmable logic controllers (PLCs*), became available in the 1970s. They are still widely used for relatively simple control applications that involve programmable logic and sequencing operations.

A major breakthrough occurred in 1975 when the first generation of *distributed control systems (DCS*) was introduced. The DCS systems consisted of networks of microprocessors and small computers that were connected to each other and to instruments by redundant "data highways". The control functions were distributed among the computers so that each computer would control a small number of process variables (e.g., 8-16 variables) but coordination among computers could still be achieved. The man-machine interface was greatly enhanced by using modern computer monitors. In the late 1970s, the first industrial applications of modern model-based control techniques were reported in France and the United States. In the mid-1980s, personal computers were introduced into the DCS systems, further enhancing the flexibility, computing power, and man-machine interfaces.

Today, the process control systems in large continuous plants typically consist of integrated networks of computers, operator workstations, instrumentation, and other control hardware. The current revolution in information technology is having a major effect on a variety of process control activities. *Smart instruments* have embedded microprocessors that perform routine signal processing activities and provide improved diagnostics. Digital communication networks such as *Fieldbus* and *Profibus* rely on open architecture and published international standards. There is increased emphasis on using computer networks to integrate process control activities with other plant and business activities, in order facilitate the effective coordination of manufacturing activities at the enterprise level.

It is somewhat surprising and ironic that despite the dramatic improvements in automation and information technology, the vast majority (85-95%) of the feedback control loops in the process industries are based on the proportional-integral (PI) and proportional-integral-derivative (PID) control techniques that originated in the 1930s. But although *advanced control techniques* are only used in a small percentage of the total control loops, the economic impact of these critical control loops is significant and justifies the additional effort. Another anomaly is that pneumatic control valves are still widely used to regulate the flow rates of liquids and gases. Thus, current process control strategies provide an effective blend of the old and the new.

4. Overview of Industrial Process Control

The operation of modern industrial plants would be very difficult, if not impossible, without automation and computer control. Safe efficient plant operation requires that thousands of process variables be controlled within specified limits. Consequently, in large chemical and petrochemical plants, thousands of process variables (e.g., temperature, pressure, flow rate, liquid level, and chemical composition) are measured on a regular basis, as often as every second or minute. Because many important product quality characteristics cannot be measured on-line (e.g., gasoline octane number, the impact resistance of plastic bottles,), samples are collected and analyzed in a quality control laboratory. Typically, samples are collected one to three times per day.

Process control relies heavily on feedback control to regulate important process variables. In large plants there may be several thousand feedback control loops which adjust approximately the same number of manipulated variables, usually flow rates, via control valves and variable speed pumps. The design of this overall process control system is a daunting task. Usually, this large control problem is decomposed into a number of smaller problems. For example, control systems can be developed for individual parts of the plant and then the individual control systems are coordinated by a supervisory control system.

A hierarchical representation of process control functions is shown in Figure 1. The lowest level represents the process, instrumentation, and associated control equipment such as control valves. At the next level, individual process variables are controlled by executing simple control algorithms, usually PI or PID control. These *regulatory control* activities are executed very frequently, as often as a fraction of a second. Process safety is also evaluated at this level. For example, each measurement is compared with pre-specified limits. If a limit is exceeded, an appropriate action is automatically taken. Thus a message might be flashed on an operator’s computer console for a minor infraction, but an automatic shutdown of equipment would occur for a more serious violation.

[Figure 1 here]

For important process control problems, advanced control strategies can provide significant benefits. These strategies are usually based on a mathematical model of the process, as discussed in Section 7. As indicated in Figure 1, the advanced control calculations are executed less frequently and produce desired values for the controlled variables (called *setpoints*) that are then used in the regulatory control calculations.

It can also be advantageous to coordinate control of individual process units (e.g., chemical reactors, distillation columns). These *supervisory control* calculations are performed less frequently, e.g., every one to four hours.

As process or economic conditions change, it may be desirable to operate the plant at a different set of conditions. This situation can arise if a different product grade must be produced or different raw materials are used. The calculation of the new operating condition is referred to as *optimization* and is shown at the next level in Figure 1. If conditions change frequently, the optimization could be done as often as every one to four hours. The top level in Figure 1 denotes the calculation of the production rates and schedules for the individual process units that comprise the entire plant.

In the following sections, emphasis will be placed on the three lowest levels in Figure 1.

4.1 Process design and process control

Historically, process design and process control have been separate activities that were carried out by different groups of people, who were sometimes in different companies. In the traditional approach, control system design is not initiated until after the plant design is well underway and major pieces of equipment have been ordered. This sequential approach can be satisfactory for relatively simple processes, and for processes that are easily controlled and do not have a high degree of integration between the individual processing units. But modern industrial plants are complex and tend to be highly integrated. Furthermore, the traditional approach has serious limitations because the plant design determines the process characteristics, as well as the operability of the plant. Thus, it is important to consider process control and plant operability issues early during plant design. There are several important reasons for doing so:

i. Ignoring control and operability issues during process design can have dire consequences. In extreme situations, the plant may be uncontrollable even though the process design appears satisfactory from a steady-state point of view. There are instances where a new plant has been constructed that met the design criteria but the plant start-up and commissioning took an inordinate period of time to complete (e.g., several years). It is a truism that even advanced process control strategies cannot compensate for a poor process design.

ii. It is easy to make small changes during process design, but difficult and expensive to make the same changes after the plant has been constructed. (e.g., the addition of a measurement port in the side of a large vessel.)

iii. Processes that are easy to control tend to have fewer problems and unplanned shutdowns.

Fortunately, during the past 20 years there has been growing industrial acceptance that process control issues must be considered early during process design.

5. Traditional Process Control Techniques

A general representation of a process control problem is shown in Figure 2. The output variables (y_1, y_2, ..., y_n) are process variables that we wish to control. For simplicity, we will assume that each output variable can also be measured. The output variables are affected by two types of input variables: manipulated variables (u_1, u_2, ..., u_m) that can be adjusted by the control system, and disturbance variables (d_1, d_2, ..., d_p) that cannot be manipulated such as ambient temperature or the composition of a raw material such as crude oil. The desired value of an output variable, the *setpoint*, will be denoted by y_{sp}. The setpoint can be either constant or time varying.

[Figure 2 here]

The general control objective is to keep the output variables at, or close to, their setpoints despite unanticipated disturbances. The most widely used control technique is *feedback control*. The basic idea is that each output variable is compared to its setpoint and then a manipulated input is adjusted based on the difference, or *error signal, e(t)*,

$$e(t) = y_{sp}(t) - y(t) \tag{1}$$

The most famous feedback control technique is the ideal proportional-integral-derivative (PID) control law,

$$u(t) = \bar{u} + K_c \left[e(t) + \frac{1}{\tau_I} \int_0^t e(t')dt' + \tau_D \frac{de}{dt} \right] \tag{2}$$

where $\bar{u}$ is a bias term and there are three adjustable *controller settings*: the controller gain K_c, the integral time τ_I, and the derivative time τ_D. Preliminary values for the controller settings are specified during the control system design but the settings are often fine tuned after the control system is installed. Equation (2) is referred to as the ideal PID control law because many variations are widely used in industry. In particular, the derivative term is often omitted to give the ubiquitous PI control law:

$$u(t) = \bar{u} + K_c \left[e(t) + \frac{1}{\tau_I} \int_0^t e(t')dt' \right] \tag{3}$$

Feedback control is very effective because corrective action is taken regardless of the type of disturbance or its magnitude. A major disadvantage of feedback control is that no corrective action is taken until the output is perturbed from its setpoint. But if an important disturbance variable can be measured, then *feedforward control* can be used in conjunction with feedback control to provide significant improvements. The important advantage of feedforward control is it provides corrective action *before* the process is upset by the disturbance. Its main disadvantage is that the disturbance variable must be measured, which is not the case for many industrial process control problems. Feedforward control has become widely used in chemical and petrochemical plants since the 1960's.

A simple representation of a combined feedforward-feedback control system is shown in Figure 3 for the situation where is only one output variable, one input variable, and one disturbance variable. The feedforward control action, u_{FF}, is based on the measured disturbance while the feedback control action, u_{FB}, is based on the error signal, e. These two signals, u_{FF} and u_{FB}, are added to form the manipulated input, u.

[Figure 3 here]

As mentioned earlier, product specifications are typically expressed in terms of quality variables, some of which cannot be measured on-line. Instead, samples are sent to an on-site laboratory on an infrequent basis (e.g., every 4-24 hours). These quality variables are monitored using *statistical quality control (SQC)* techniques, which are also referred to as *statistical process control (SPC)* techniques. The SQC methodology relies on *quality control chart*s. The simplest quality control chart, the Shewhart chart, is shown in Figure 4. Measurements of a quality variable are plotted versus time and compared with specified upper and lower limits. If a measurement exceeds a limit, the process performance is considered to be unsatisfactory and an attempt is made to determine the root cause of the problem. Unlike feedback and feedforward control, SQC does not provide an immediate correction action. Thus, it is more of a monitoring technique that a control strategy.

Nevertheless, it is widely used in manufacturing plants to ensure that product specifications are satisfied.

[Figure 4 here]

6. Control System Design

The development of a control system begins with a critical decision, the formulation of the control objectives. The control objectives are based on management objectives for the process; process knowledge and experience; and the operational requirements for the process. Although the specific control objectives vary from plant to plant, there are a number of general requirements:

1. *Safety.* It is imperative that industrial plants operate safely so as to promote the well being of people and equipment within the plant, as well as in the nearby communities. Thus plant safety is always the most important control objective.
2. *Environmental Regulations.* Industrial plants must comply with environmental regulations concerning the discharge of gases, liquids, and solids beyond the plant boundaries.
3. *Product Specifications and Production Rate.* In order to be profitable, a plant must make products that meet specifications concerning quality and production rate.
4. *Economic Plant Operation.* It is an economic reality that the plant operation must be profitable. Thus the control objectives must be consistent with economic objectives. For example, if a plant can sell all of its product, then it would be desirable to maximize the production rate. But in a market-limited situation, it might be more important to reduce manufacturing costs (e.g., utility or raw material costs).
5. *Stable Plant Operation.* The control system should facilitate stable plant operation without excessive oscillations in key process variables. Thus it is desired to have smooth set-point changes and rapid recovery from plant disturbances (e.g., changes in feed composition).

After the control objectives have been formulated, the control system can be designed. The design problem consists of four main steps:

1. Divide the overall control problem into smaller problems of a more manageable size.
2. Select the process variables that are to be controlled, manipulated, and measured.
3. Choose a control strategy and a control structure.
4. Specify the controller settings.

For large industrial plants, the overall control problem involves thousands of process variables that must be measured or controlled. It is not feasible to design one large control system for ths plantwide control problem. Instead, the overall control problem is decomposed into a number of smaller problems of more manageable size. This decomposition can be based on the arrangement and interactions between individual processing units such as chemical reactors, distillation columns and heat exchangers. However, the decomposition is rather subjective and will be influenced by the experience and preferences of the control system designer.

In Step 2 of the design strategy, the choice of the controlled, manipulated, and measured variables is largely dictated by the control objectives. For Step 3, it is convenient to distinguish between two general types of control strategies. In a *decentralized control strategy*, there is a separate controller (usually PI or PID) for each controlled output. Consequently, this strategy is also called *multi-loop control*. By contrast, in *centralized control* there is a single controller that simultaneously controls all of the outputs by adjusting all of the inputs. Decentralized control is the traditional approach and is much more widely used. However, for difficult control problems, centralized control strategies such as *Model Predictive Control* (Section 7.1) can be very advantageous.

A key design decision for multi-loop control is to determine an appropriate *control structur*e, i.e., to find a suitable pairing of controlled and manipulated variables. This decision is based on knowledge of the process, and static and dynamic models of the process, if these models are available.

The final step in the control system design is to specify the controller settings. For example, if PI control is considered, the controller gain, K_c, and the integral time, τ_I, in Eq. (3) would be assigned nominal values. The controller settings can be adjusted (or "tuned") after the control system is installed, if the nominal values prove to be unsatisfactory.

7. Advanced Control Techniques

For the vast majority of process control problems, the traditional control methods of Section 5 work well and thus there is little incentive to consider more "advanced control" methods. But there are classes of difficult process control problems where an advanced control strategy can provide much better control. These problems typically involve critical process variables that strongly affect key control objectives such as safety, product quality, process operability, and compliance with environmental standards. Thus the economic impact can be significant.

Advanced control techniques can provide significant improvements for process control problems that have one or more of the following characteristics:

1. Strong interactions between process variables;
2. Strongly nonlinear behavior;
3. Long time delays;
4. Frequent, unanticipated changes in the process characteristics;
5. Inequality constraints on process variables

To illustrate the concept of process interactions, consider the process diagram in Figure 2. In general, each manipulated input affects *all* of the controlled outputs. If a decentralized (multi-loop) control strategy is used, each input is adjusted based on only a single output. But this corrective action can adversely affect the other outputs if the process interactions are quite strong. In these situations, a decentralized control strategy such as model predictive control (see Section 7.1) can provide significant improvements.

If the process is highly nonlinear, then its static and dynamic characteristics depend on the current operating conditions. If the process characteristics are known, the controller characteristics can be changed accordingly, in order to achieve good control system performance. This type of control strategy is referred to *as nonlinear control*. As a simple example, the controller gain, K_c, in Eqs. (2) or (3) could depend on y(t) or e(t), instead of having a constant value. This nonlinear control technique is referred to *gain scheduling*. But if the process characteristics change in an unpredictable manner, an *adaptive control* strategy can be very useful. Nonlinear control strategies are described in the references while adaptive control strategies are considered in Section 7.2.

A *time delay* results in a delay of information. For example, if takes 15 minutes to measure the composition of a chemical mixture, a time delay of 15 minutes is said to occur. Time delays are also associated with the flow of fluids in pipelines and the movement of solids using equipment such as conveyor belts. Because time delays have a detrimental effect on feedback control, special model-based control techniques have been developed for control problems with long time delays.

The basis concept for *time delay compensation techniques* such as the *Smith Predictor* is that a process model is used to predict the value of an output variable, one time delay ahead. Then the control calculations are based on the predictions as well as the current measurements.

A key feature of many industrial control problems is that process variables must be maintained between upper and lower limits in order to ensure safe, efficient plant operation. For example, the temperature or pressure in a closed vessel must not exceed a metallurgical limit. Also, it is common to require that a chemical impurity level be below a specified limit that is determined by environmental regulations or product quality requirements. Such inequality constraints can be accommodated by *selective & override control systems* or by Model Predictive Control.

7.1 Model Predictive Control

In the chemical and petrochemical industries, *Model Predictive Control (MPC*) has become the most widely used advanced control technique for difficult control problems. The basic idea can be summarized as follows. If a reasonably accurate dynamic model of the process is available, then the model and current measurements can be used to predict the future process behavior. The control calculations are based on both predictions and measurements. The values of the manipulated inputs are calculated so that they minimize the difference between the predicted response of the controlled outputs and the desired response. Model predictive control offers several important advantages:

i. The manipulated inputs are adjusted based on how they affect the outputs;
ii. Inequality constraints on process variables are easily incorporated into the control calculations;
iii. The control calculations can be coordinated with the calculation of optimum setpoints;
iv. Accurate model predictions provide an early indication of potential problems.

The first versions of MPC were developed independently in the 1970's by two industrial research groups: Shell Oil in the United States and ADERSA in France. During the past 20 years, MPC has had a major impact on industrial practice with over 3000 applications worldwide, primarily in oil refineries and chemical plants. Large MPC applications can have as many as 40 controlled outputs and 20 manipulated inputs.

Model predictive control is widely considered to be the control method of choice for challenging multivariable control problems in the chemical and petrochemical industries. One reason why MPC has become a major commercial success is that there are over 15 vendors worldwide who are licensed to market MPC products and who install them on a turnkey basis. Consequently, even medium-sized companies have been able to take advantage of this new technology. Payout times of 3-12 months have been widely reported.

Experience has indicated that the identification of the process model is a key step in the successful implementation of MPC techniques. In most MPC applications, special plant tests are required to develop empirical dynamic models from input-output data. These tests can be very time-consuming, involving around the clock tests for days or even weeks. But the benefits from implementing MPC generally justify this short-term disruption to normal plant production.

7.2 Adaptive Control

For conventional PID control systems, it may be necessary to re-tune the controller if a significant process change occurs. On-line controller tuning traditionally requires time-consuming plant tests. If the process changes are frequent and largely unknown, then *auto-tuning* or *adaptive control* techniques should be considered. Auto-tuning methods for PI and PID controllers, such as *relay auto tuning*, are commercially available. They are usually based on a single plant test.

In adaptive control, the controller settings are adjusted automatically to compensate for changing process conditions. The adaptation can be performed continuously, intermittently, or upon demand, similar to an auto-tuning system. The design of an adaptive control system is often based on a *self-tuning regulator* approach. The basic idea is that the parameters in a process model are updated as new data is obtained. Then the controller settings are adjusted based on the new values of the model parameters.

Commercial adaptive controllers have been available since the 1980s. However, they appear to have had less impact on chemical and petrochemical plants than either MPC or auto tuning.

Glossary

Adaptive Control: The controller settings or control configuraton is automatically adjusted to compensate for changing conditions.

Centralized Control: Each manipulated variable is used to control a single controlled variable.

Decentralized Control: The manipulated variables are coordinated to control all of the controlled variables.

Error Signal: The difference between the desired value and the measured value of a controlled variable.

Feedback Control: The controlled variable is measured and compared to its desired value. The manipulated variable is adjusted based on this difference.

Feedforward Control: The disturbance variable is measured. The manipulated variable is adjusted based on this measurement.

Model: A mathematical description of the process that shows the relationship between important process variables.

Model Predictive Control: A dynamic model of the process is used to predict future values of the controlled variables. The manipulated variables are adjusted based on the predictions, as well as current measurements.

Multi-loop Control: A synonym for decentralized control.

Process: A physical or chemical operation. (The system to be controlled.)

Process Control: The regulation of key process variables such as temperatures, pressures, flow rates, stay at (or near) their desired values.

Setpoint: The desired value of a controlled variable.

DCS: Distributed Control System

MPC: Model Predictive Control

PID: Proportional-Integral-Derivative

PLC: Programmable Logic Controller

SQC: Statistical Quality Control

Summary

The operation of modern chemical and petrochemical plants would be very difficult, if not impossible, without automation and computer control. Safe efficient plant operation requires that thousands of process variables be controlled within specified limits. Today the typical process control system in a large continuous plant is an integrated network of computers, operator workstations, instrumentation, and other control hardware. Although the traditional PI and PID control algorithms are the most widely used control techniques, advanced control methods such as model predictive control can provide significant improvements for difficult multivariable control problems.

During the past 20 years, the chemical and petrochemical industries have faced major challenges due to global competition and rapid changes in economic conditions. Consequently, there has been increased emphasis on operating plants more efficiently and economically. For the past 20 years, advanced automation, process control, and on-line optimization have played key roles in improving plant performance. Today there is increased emphasis on using computer networks to integrate process control activities with other plant and business activities, in order facilitate the effective coordination of manufacturing activities at the enterprise level.

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