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Costas Kravaris , Ioannis K. Kookos
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1 Introduction

STUDY OBJECTIVES

After studying this chapter, you should be able to do the following.

- Identify the underlying reasons for the need of control systems.
- Identify the main parts of a feedback control system.
- Identify the main terminology and notation used in process control.
- Discuss recent history of process control.

1.1 What is Process Control?

Automatic control is a discipline which studies the design of man-made systems with the aim to “shape” purposefully their response. Scientists and engineers who work in this field of study, depending on their background or their area of interest, may give a more specific or more abstract definition. Automatic control is an interdisciplinary science and plays a key role in most engineering disciplines including electrical, mechanical and chemical engineering. There is a common theoretical basis that can be applied to all these systems, despite the major differences in their physical characteristics.

Process control is the branch of automatic control concerned with production plants in the chemical, petrochemical, food and related industries. Process control plays a critical role in ensuring proper operation of the plant, in terms of safety, product quality and profitability. Even though chemical processes are of different physical nature when compared to robots, unmanned vehicles and aircrafts, missiles and spacecrafts, the underlying principles of automatic control are the same.

Automatic control is a part of our everyday life. Cars, refrigerators, washing machines, public buildings and homes have numerous automatic control systems installed. What is equally impressive is that these control systems operate and function so efficiently that we hardly ever take notice of their existence. They deliver, they are reliable, they make our everyday life better and safer, and they are really cheap. They are the result of the hard work of numerous ingenious scientists and engineers who devoted their life to make our world a better place to be.

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The amount of knowledge that has been generated in the past 100 years in the field of automatic control is vast. Using this knowledge to design and operate control systems in practice is vital for maintaining the same pace of development in the years to come. This book aims at explaining the fundamental principles of process control in a way that makes it easier for future chemical engineers to comprehend past developments and to develop new tools that advance engineering practice. We also hope that learning process control methods and concepts will help future chemical engineers to interact and collaborate with control engineers of other disciplines.

1.2 Feedback Control System: Key Ideas, Concepts and Terminology

The idea of feedback control will be introduced in the present section, along with some pertinent key concepts and terminology.

Consider the primitive control system shown in Figure 1.1. A liquid stream is fed to a buffer tank (*process*) and an operator (*controller*) tries to keep the liquid level in the tank (*measured* and *controlled variable*) at the desired value (*set point*) by using a logical procedure (*control algorithm*) based on his/her training and experience. The means to accomplish this task is the opening or closing of a valve (*final control element*) that adjusts the flowrate (*manipulated variable*) of the exit stream.

A number of questions are immediately raised.

- Why does the liquid level vary during everyday operation?
- What is the "desired level" of the liquid in the tank and on what grounds is it determined?

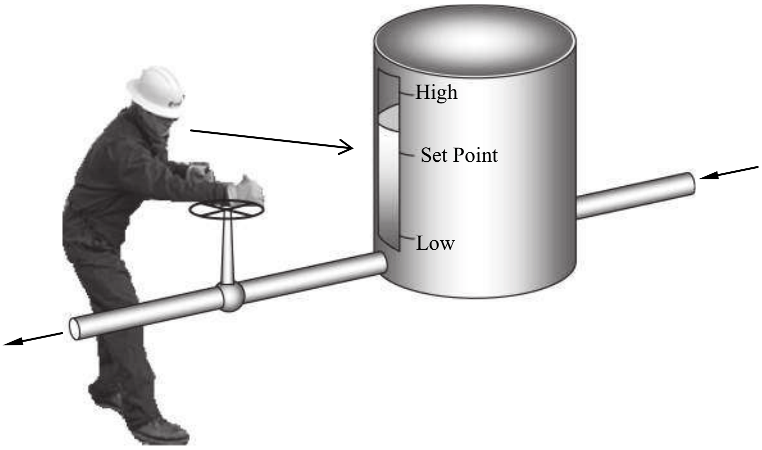

Figure 1.1 A "primitive" level control system.

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- What is the best sequence of actions that the operator needs to take when the liquid level deviates from the set point?
- Do we need a human operator to control the level? Why not build an “automated system”?
- Would an “automated system” be more efficient and reliable than the human in controlling the level of the liquid?
- Are there any other measurements that could be used, in combination with the level of the liquid in the tank, in order to more effectively maintain the liquid level at the desired value?

Some of these types of questions have an easy answer, but some will need further thinking and elaboration throughout your process control course and even throughout your professional career.

Most undergraduate courses in chemical engineering consider processes that operate at steady state. This is a logical and well-documented simplification that allows chemical engineers to design fairly complex processes in a reasonable amount of time. However, in actuality, processes operate in a dynamic environment. Imagine that you design a heat exchanger that uses sea water as cooling water to cool down a process stream from 100 °C to 50 °C. At the design stage you have to make an assumption about the temperature of the cooling water (a unique value) and suppose that you have selected a temperature of 20 °C. Now think about the chances of the cooling water temperature being exactly 20 °C. Will the system fail if the actual temperature of the water is 15 °C or 10 °C? The answer is yes, the system will fail to keep the temperature at the desired value of 50 °C, unless a valve is installed, which can appropriately adjust the flowrate of the cooling water. In addition, a temperature sensor needs to be installed, to measure the temperature of the process stream exiting the heat exchanger. Then, using the measured and recorded temperature, an operator can check if the temperature is at the proper value, and appropriately adjust the cooling water flowrate to correct any discrepancies, as shown in Figure 1.2. The sea-water temperature can vary

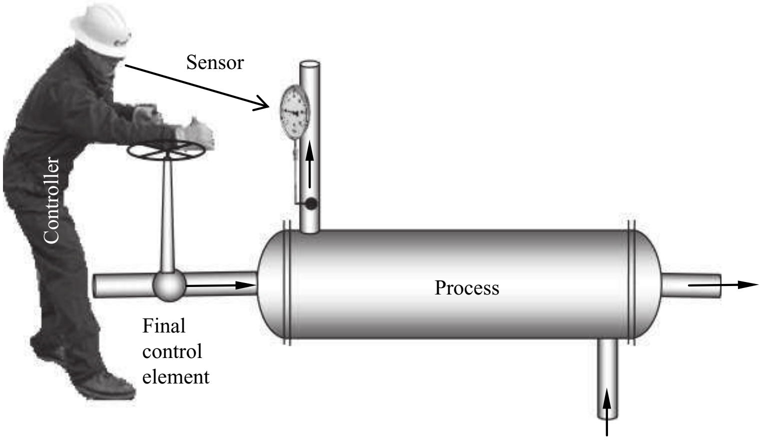

Figure 1.2 A “primitive” temperature-control system.

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throughout the day, so the operator will need to perform frequent adjustment of the valve opening to keep the temperature of the process stream close to the desired temperature. In addition, the operator can implement changes in the desired temperature, if there are reasons related to the operation of downstream processes.

The basic elements of the temperature-control system shown in Figure 1.2 are also shown in the block diagram of Figure 1.3. The blocks are used as a means of representing the components of the system and the arrows denote a signal or information flow. The measurement (the line exiting the sensor and entering the controller) is not, in the case of the control system of Figure 1.2, an actual signal but an information flow and denotes the reading of the temperature indication by the operator. The operator/controller is a necessary element of the loop that processes (using a control algorithm) the information and decides on the appropriate action to be taken (opening or closing of the valve). The opening or closing of the valve determines the flowrate of the cooling medium (sea water) and thus the rate of heat transfer in the heat exchanger. Finally, the temperature of the product stream is measured by the sensor (operator's eyes) and the loop is closed. In most cases, the controller is a computer-based system that receives a signal from the sensor, executes the control algorithm and sends a signal that sets the valve position, as indicated in Figure 1.4. Computers can perform very complex calculations in a very short time, can handle more than one control system simultaneously and work continuously and, in most cases, without human intervention.

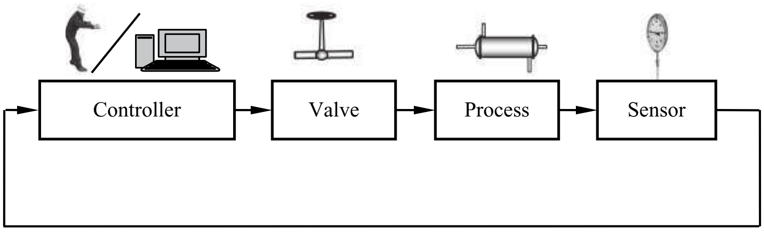

Figure 1.3 Elements of a "primitive" temperature-control system.

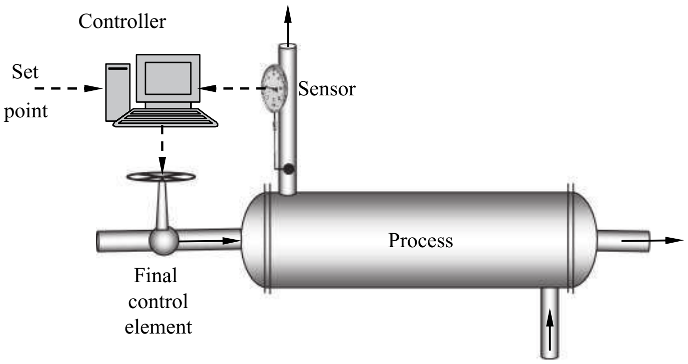

Figure 1.4 A computer-based temperature-control system.

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Let's now summarize the types of process variables encountered in the primitive control systems that we have seen so far.

Disturbance variables. Any process is affected by several external influences, and many of them vary in an uncontrollable and unpredictable manner. These are the disturbances that cause the operation of the process to deviate from the desired steady state. In the case of the heat exchanger, potential disturbances are the sea-water temperature, the temperature and the flowrate of the incoming process stream, or equipment aging known as fouling (which increases the resistance to heat transfer). Some of the disturbances could be measured in real time but others are difficult, expensive or even impossible to measure.

Manipulated variables. The manipulated variables are those process variables that are adjusted by the controller in order to achieve the control objectives. A manipulated variable is also called control input, to signify that it represents the control action that "feeds" the process. The most frequent manipulated variable in the chemical process industries is the flowrate through the installation of a control valve or a pump.

Measured variables. Measured variables are all the variables for which we have installed a sensor or measuring device that continuously measures and transmits the current value of the variable. Of course, sensors cost money and need frequent maintenance, therefore their installation should be well justified. The most common measured variables in the chemical industries are temperature, pressure, flow and level. Others, such as composition, are more costly and less frequently used.

A measured variable that the controller is maintaining at a particular desired value is called a **controlled variable**. The desired value is called the **set point** of the controlled variable. The set point is usually kept constant for a long time, but sometimes a need may arise to change the set point, and this should be handled by the controller.

When the value of the controlled variable agrees with its set point, it is "in control," otherwise there is an error. The **error** is defined as the difference between the set point and the value of the controlled variable, and the job of the controller is to make it equal to zero.

Figure 1.5 depicts a generic feedback control system. It shows all the types of variables that come into play, as well as the basic elements of the control system and how they are connected with each other.

The final control element (usually a control valve) together with the process and the sensor comprise the **physical system** or **open-loop system**. We see from Figure 1.5 that, when the sensor is connected to the controller, and the controller is acting on the final control element, the overall system has a circular structure, like a ring or a loop, and it is called the **closed-loop system**. It is also called a **feedback control system**. The idea of feedback control involves continuous monitoring of the controlled variable and "feeding back" the information, to make changes and adjustments in the process, through changes in the manipulated variable. The controller's action is usually based on the error, i.e. the discrepancy between the set point and the measurement of the controlled output. Depending on the error (its current value, its history and its trend), the controller takes corrective action. In simple terms, one can describe the operation of a feedback control system as: monitor, detect and correct.

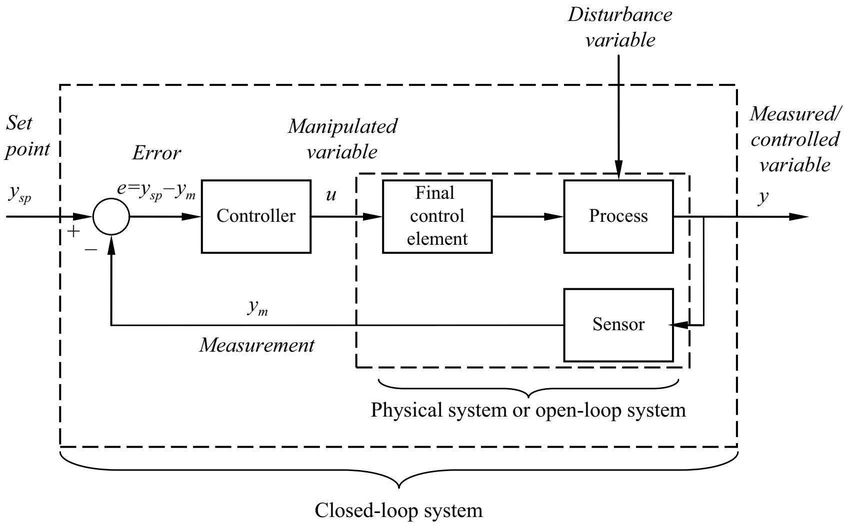

Figure 1.5 Basic elements of a feedback control system and their interconnections.

Sensors play a critical role is the proper operation of a feedback control system. Sensors use an electrical or mechanical phenomenon in order to determine the temperature, pressure, level or flowrate. Temperature sensors are based on the expansion of a liquid or gas (thermometers), on the Seebeck or thermoelectric effect, the creation of voltage between two junctions at different temperatures (thermocouples), the variation of electrical resistance of several materials with temperature (resistance temperature detectors and thermistors) and the thermal radiation emitted (pyrometers). Most pressure sensors are based on measuring the deflection or strain caused by the pressure when applied to an area (strain-gauge, electromagnetic, piezoelectric, etc.). Pressure sensors are used in conjunction with an orifice or a Venturi tube to measure flow, as differential pressure across the orifice or between two segments of a Venturi tube (with different aperture) is strongly related to flow. Pressure sensors are also used to calculate the level of a liquid in a tank as the pressure difference between the top and the bottom of a tank is directly proportional to the height of the liquid. The transmitter is used to convert the primary measurement by the sensor to a pneumatic or electrical signal. The combination of the sensor and the transmitter is called a transducer.

In a chemical plant, there may be hundreds or thousands of feedback control loops like the one depicted in Figure 1.5. The need to transmit all information and functionality to a central "control room" (see Figure 1.6) to achieve continuous monitoring and reduce drastically the manpower required was quickly identified and implemented in the 1960s. This centralization was really effective in improving the operation of the plant. At that time, the controllers (one controller for each control loop) were behind the control room panels, and all control signals were transmitted back to plant. Gradually the structure was modified as all functionalities were assigned to a network of input/output racks with their own control processors which could be distributed locally in the plant (and could communicate with the

Figure 1.6 A control room of the 1960s and a more recent DCS control room (from Wikimedia Commons, the free media repository).

control room). The distributed control system or DCS was thus born, in which the controllers were placed close to the processing units but transmitted all information to a central location through a central network to minimize cabling runs. Monitoring, interconnection, reconfiguration and expansion of plant controls were finally easy. Local control algorithms could be executed by the central units in the case of system failure and thus reliability was greatly enhanced. Recent advantages such as wireless technology and Internet of Things as well as mobile interfaces might have a real impact in the near future.

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1.3 Process Control Notation and Control Loop Representation

The standard notation used in process control is also indicated in Figure 1.5. The actual value of the measured and controlled variable is denoted by y. The measurement is denoted by y_m, and this may not match y in a transient event, as the sensor signal may be lagging behind in the changes of the physical variables that it measures. The desired or set-point value of the controlled variable is denoted by y_{sp}. The error signal $e = y_{sp} - y$ is also indicated in the diagram. (The small circle with the two inward arrows with appropriate signs and one outward arrow indicates the subtraction operation.) The error signal e drives the controller, which determines the appropriate adjustments, in order to correct the error and eventually bring it back to zero. The signal u from the controller sets the value of the manipulated variable of the process, which is actually implemented by the final control element. Finally, the sensor detects the change in the response of the system and the loop is closed.

Process engineers use standard symbols to denote process units such as vessels, heat exchangers and towers when constructing the Process Flow Diagram (PFD) of a production facility. The same holds true for control and instrumentation engineers. The standards for documenting the details of control and instrumentation have been defined by the Instrumentation, Systems, and Automation Society (ISA) and are known as Standard ISA-S5. There are several publications by the ISA that document in great detail the construction of Process and Instrumentation Diagrams (P&ID) that are routinely used by process engineers during the construction, commission and operation phases. The reader is referred to these publications as they are outside the scope of this book.

The notation that will be used in this book is presented in Figure 1.7 through an example. The standard representation of a control system is shown in this figure. A process stream

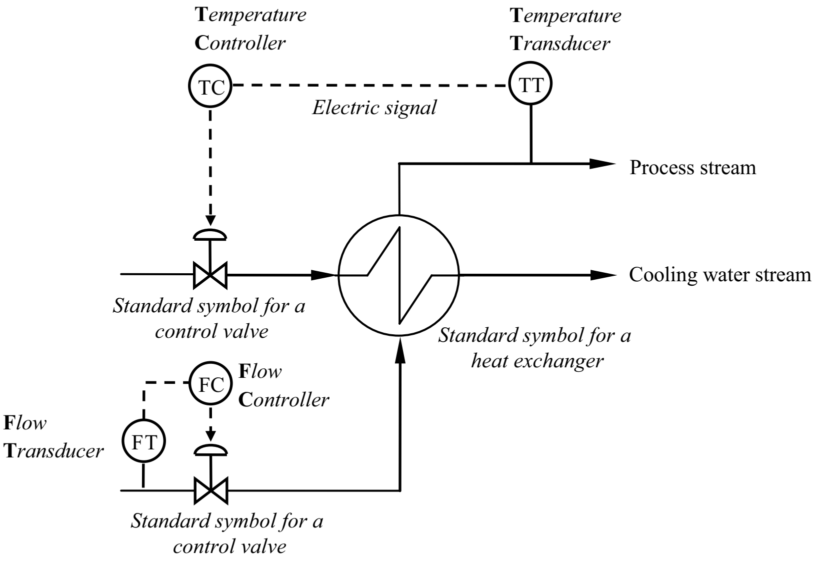

Figure 1.7 Common control loop representation.

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that is flow-controlled, is cooled using a heat exchanger and cooling water. The temperature of the outgoing process steam is measured by a temperature sensor and the measurement is indicated by the temperature transducer (TT) symbol in Figure 1.7. Bubble or circle symbols are used to indicate instrumentation (measurement) or control function. Inside the circle symbol a two-letter coding system is used to denote the specific functionality of the block. The first letter in the two-letter naming system refers to the variable controlled or measured and the letters commonly used are the following.

T: temperature
F: flow, flowrate
L: level
P: pressure
C (or A): composition

The second letter indicates whether this is a measuring device or transducer (T) or a control device (C). TC is therefore used to indicate a temperature controller while FC indicates a flow controller in Figure 1.7. The two circle symbols denoted as TT (temperature transducer) and TC (temperature controller) are connected through a dashed line (– – – –) which indicates an electrical signal (4–20 mA, 1–5 V or 0–10 V). Other common conventions are the following: a pneumatic signal is denoted by —//—//— (normally in the range of 3–15 psig) and a data-transfer signal is denoted by —o—o— (usually binary signal). We will not try to indicate explicitly whether a signal is electrical or pneumatic, as it adds a complexity that is unnecessary within this book, and we will be using a dashed line to indicate exchange of information between a sensor, a controller and a final control element, as shown in Figure 1.7.

1.4 Understanding Process Dynamics is a Prerequisite for Learning Process Control

The action of a controller is not static: it is dynamic in nature. As external disturbances vary with time, the controller must take action, in a continuously changing environment. And the controller is not isolated: it keeps interacting with the sensor and the final control element, which in turn interact with the process, and all these interactions are transient in nature. To be able to understand what is happening inside the feedback control loop, we must first have a thorough understanding of transient behavior.

The process, the final control element, the sensor and the controller are all dynamic systems, whose behavior changes with time due to a changing environment (such as varying feed composition or temperature), changing process specifications (such as changing product purity) or equipment aging (such as fouling). The mathematical tools normally used to describe process dynamics are ordinary and partial differential equations accompanied, in some cases, by algebraic equations.

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In the first part of this book we will study the dynamics of an isolated system, to try to understand its transient behavior. We will see different kinds of transient behavior, and we will explain the behavior and characterize it in a systematic way. We will see how to calculate these transient responses, analytically and numerically. One of the key concepts that we will discuss is the concept of stability, and we will derive tests to determine if a system has stable behavior. We will also introduce the necessary software tools to calculate routinely the dynamic response of common process systems.

Equipped with these concepts and tools, we will study interconnected dynamic systems, in a feedback control loop. We will see how the dynamic behavior of all the elements of the loop can be combined, and we will derive the dynamic behavior of the overall system, and calculate its transient response.

Typical process systems' dynamic responses are presented in Figure 1.8. The response can be fast or relatively slow as shown in Figures 1.8a and b, respectively. A characteristic commonly encountered in process systems is that of delayed response as shown in Figure 1.8c. These three general responses are the ones usually obtained by chemical processes like distillation and absorption columns, evaporators and heat-transfer equipment. There are

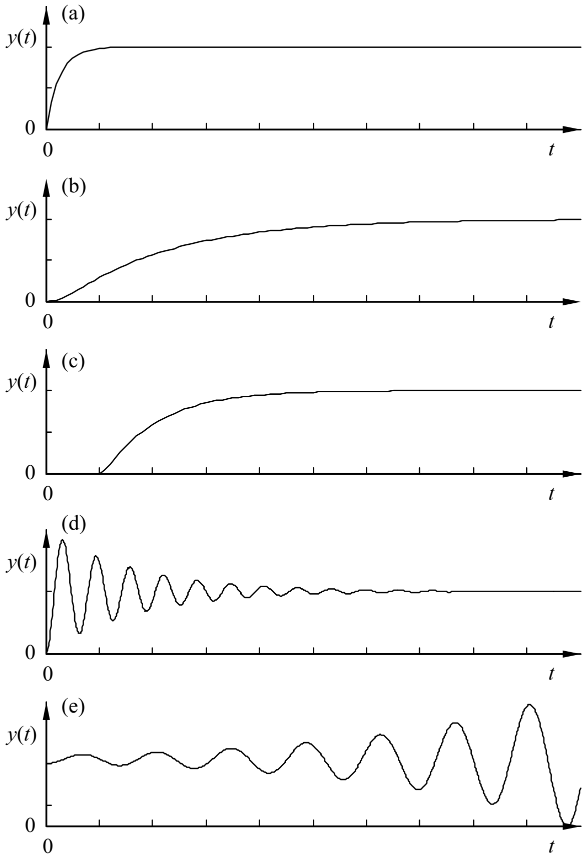

Figure 1.8 Representative cases of process system transients: (a) fast transient, (b) slow transient, (c) delayed transient, (d) oscillatory transient and (e) unstable transient.