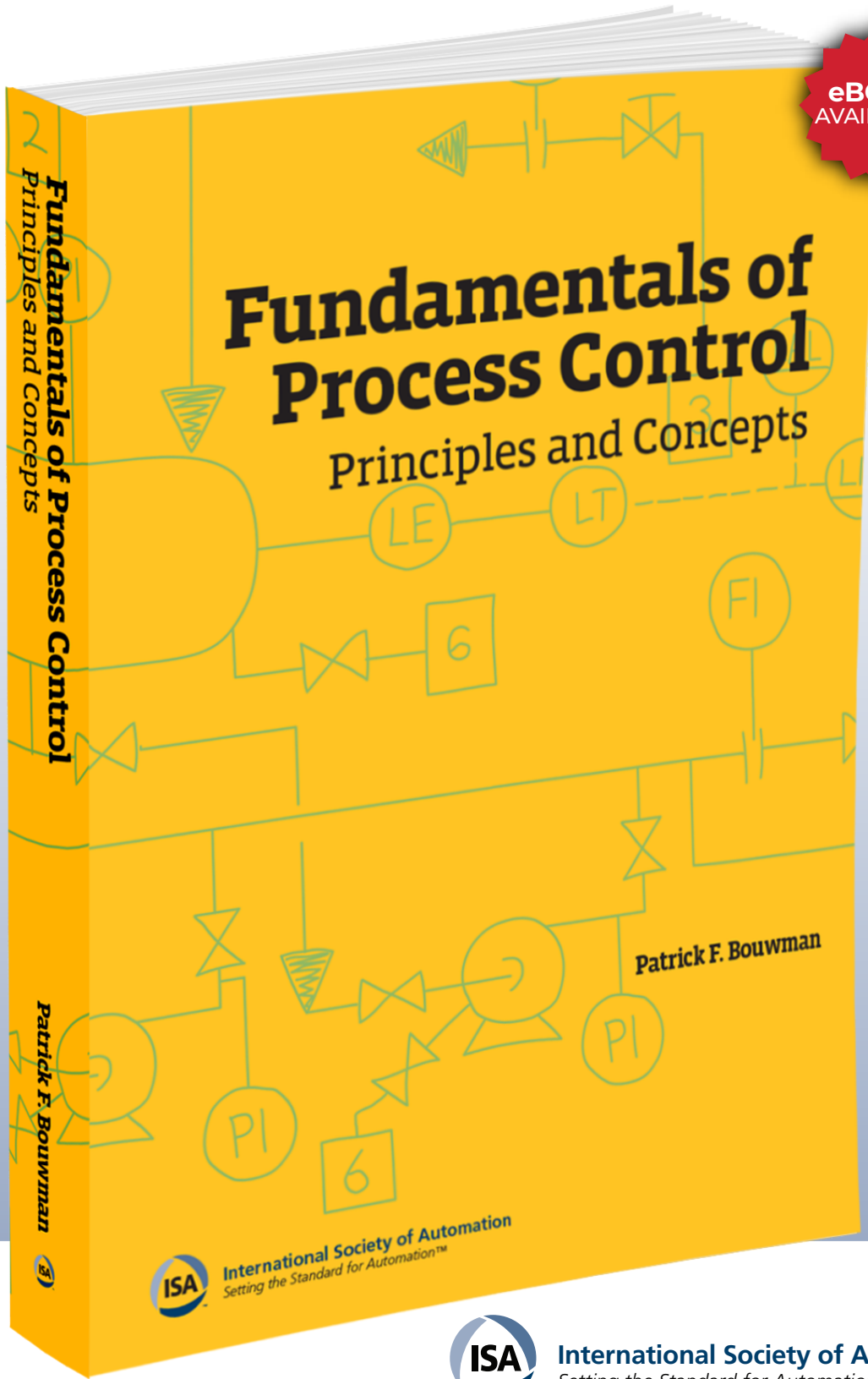
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Fundamentals of Process Control

Principles and Concepts

By Patrick F. Bouwman



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Preface

The evolution of instrumentation and industrial process control has led to today's intricacies of computers, microcontrollers, distributed control systems, and sophisticated networks of intelligent devices. They are all connected to human-machine interfaces, either directly or through wireless networks and handheld devices. The fundamental scientific principles on which process control is based are unchanged. Today, they are better understood in the academic and scientific communities, but they have been neglected in the study and application of process control in pursuit of applying the latest technologies.

There is considerable variation in the hardware and software available from vendors and in the application and practice of these scientific principles from one industry to another. The material presented in this book is generally oriented toward the automation practitioner in such processing industries as petroleum, petrochemical, chemical, pulp and paper, mining, power, drug manufacturing, food processing, and water/wastewater treatment.

This book is designed to teach the fundamental principles, concepts, and theory of process control and to provide detailed examples of how they are applied in controlling industrial processes.

It is designed for both those who want to study independently and those who are studying at a college or university. It also serves as a reference resource for engineers, senior technicians, technologists, and first-line supervisors who are working in or involved in the field of process control.

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Much of the book's content is based on my many years of teaching process control at the college level. Therefore, each chapter can be considered a lecture or presentation of a specific process control topic. By reading each chapter, students can deepen their understanding of the subject. However, for those who have some prior knowledge of process control, the chapters can be read and studied independently or used as a reference for the topic covered. This modular approach also allows college and university instructors to select specific chapters and the appropriate sequence to tailor their course material.

There are no specific prerequisites for this study, though an appreciation for industrial concerns and their philosophies will be helpful. It is inevitable that parts of the text will involve mathematics. However, the student does not need to be intimately familiar with such mathematics beforehand to appreciate the fundamental principles and concepts that are presented and applied here. Often, mathematics becomes one of the barriers that prevent people from understanding and using fundamental principles. I have attempted to minimize such barriers by providing detailed worked examples to help students understand the mathematics used. Engineering students will recognize these examples and appreciate why mathematics is part of the engineering curriculum.

Organization and Sequence

The text has been divided into three sections reflecting Principles and Concepts (Chapters 1 through 10), Control Strategies (Chapters 11 through 17), and Advanced Topics (Chapters 18 through 22). This allows the text to be used as a two- or three-semester course at a technical college or university.

The book is also divided into 22 chapters, each of which builds on the content of the previous chapter to expand the reader's understanding of the subject.

- Chapter 1 – A broad introduction to process control, its intent, and why it is important to understand and study process control
- Chapters 2 through 4 – The most fundamental concepts encountered in process control
- Chapter 5 – Process dynamics
- Chapter 6 – Process characteristics
- Chapter 7 – Sensors and transmitters, and the importance of the accuracy, precision, sensitivity, and validity of measurements
- Chapter 8 – Final control elements

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About the Author

Patrick F. Bouwman is a semiretired electrical engineer with over 40 years of industrial experience, including 18 years in the design and development of military electronics, instrumentation, and biomedical equipment. For more than 15 years, Bouwman operated his own company specializing in research, design, and development of data acquisition and signal processing systems for medical research applications and the instrumentation and process industry. He has provided design and consulting services to the process and automation industry and participated in research conducted at McGill University by custom designing data acquisition equipment and instrumentation for medical research applications.

In addition, Bouwman taught industrial electronics at the collegiate level for over 20 years and was department chair for 16 years, a role in which he was actively involved in all facets of curriculum development, laboratory design, industrial training, and continuing education. He has written numerous instructional and lab manuals on topics including analog and digital electronics, signal processing, discrete automation, instrumentation, process control, PLC programming, ISA-5.1 technical documentation, robotics, computer automation, distributed automation, and medical and military electronics.

He has also provided technical training and instructional material to the Canadian Armed Forces; conducted seminars in data acquisition, signal processing, instrumentation, and control for the manufacturing industry; and prepared and conducted

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seminars/workgroups in instrumentation, process control, and ISA-5.1 for the International Society of Automation (ISA) Montreal Section.

Bouwman is a senior member of ISA, and he served on the Montreal Section board of directors.

He received a B.Sc. in electrical and electronic engineering from Concordia University in Montreal in 1976, and he currently lives in Montreal, Canada.

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Section 1

Principles and Concepts

This section (Chapters 1 through 10) is intended to teach the student the fundamental principles and concepts in feedback control and the functional methods that are used in the process control industry.

Chapter 1 gives a broad introduction to what process control is, its intent, and why it is important to study process control. It also outlines some of the scientific and mathematical principles that are fundamental to understanding process control. The chapter ends with a discussion of process variables, specifically temperature, pressure, and flow.

Chapters 2 through 4 introduce the most fundamental concepts encountered in automated process control, namely the control loop and basic terminology. The concept and mathematics of block diagrams and the transfer functions are introduced to describe and analyze the functional structure of a feedback control loop. Combining transfer functions with block diagrams provides the tools needed to understand more complex systems.

System dynamics are the ways a system reacts to a change in set point, load, or disturbances. Chapter 5 describes many of the general concepts and principles of system dynamics and the associated terminology.

Chapter 6 describes the characteristics of process and the relationship between the manipulated variable (input) and the controlled variable (output). This chapter also lays the foundation for Chapter 18, "Process Modeling and Simulation," in Section 3.

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One of the most critical aspects in designing and installing a feedback control loop is specifying the measuring system that will obtain a measurement of the controlled variable. Chapter 7, "Sensors and Transmitters," defines and explains accuracy, precision, sensitivity, and the validity of measurements and transmission systems used in process control.

Final control elements have a direct influence on the process by converting the control signal generated by the process controller into the action required to correctly manipulate the process to meet its desired value. Chapter 8 covers some of the fundamental principles of final control elements and actuators, such as control valves, motors, pumps, and solenoids.

Chapter 9 discusses process controllers, the element of the process control loop that processes the information needed to perform the decision-making function. A clear understanding of the computational aspect of the controller is necessary for proper use and tuning of the process control loop.

A properly tuned control loop maintains its process value at its desired set point, regardless of external disturbances. Chapter 10 discusses the process of tuning control loops by setting the proportional, integral, and derivative values to get the best possible control.

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1 Introduction and Overview

Welcome to *Fundamentals of Process Control*. The purpose of this book is to provide the reader with an introduction to the fundamental principles, concepts, and techniques of process control. It is designed specifically for students in technical schools who are studying automation; however, students in related fields can benefit from understanding the theories and practices that form the body of knowledge that is process control.

The field of process control encompasses many diverse disciplines, scientific principles, and mathematical concepts. This book touches on each of these in order to help the reader develop a basic understanding of automated process control.

Learning Objectives

- Have an appreciation of process control history
- Understand the meaning of process control
- Recognize the importance of process control
- Become familiar with process control terminology
- Recognize the fundamental concept of differential equations
- Become familiar with the principle of thermodynamics

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1.1 History

Automated control systems date back thousands of years. The first feedback control device on record is thought to be the ancient water clock of Ktesibios in Alexandria Egypt around the third century BC. It kept time by regulating the water level in a vessel and, consequently, the water flow from that vessel.

The first well-defined use of feedback control seems to have been James Watt's application of the flyball governor to the steam engine in about 1775. Broader use of automatic control began in the late 1920s, and the first general theoretical treatment of automatic control was written by Harry Nyquist in 1932. The growth in industrial use of automated process control has been steady and consistent.

As new scientific principles were discovered and new technologies implemented, many of these new principles and technologies were applied to process control hardware and software. The industrial use of automation technology has developed and advanced over the past decades and continues to advance into the digital age.

The underlying principles of automated control have kept pace and also developed rapidly. A constructive and broad basis of understanding has been formed, and new ways of controlling processes have been developed. Today's applications are based on this foundation. New approaches to automation and control, such as distributed control, statistical process control, fuzzy logic control, and internet applications such as the Industrial Internet of Things (IIoT) and artificial intelligence (AI), are becoming more entrenched in the industry.

Two important examples of new approaches are the application of analog electronics to replace mechanical controllers, and then the introduction of the digital computer and microprocessor to process control. As a result, automation and control has received a significant and special boost from technology.

The underlying principles and theory of process control have also developed steadily, and a firm and broad foundation of understanding has been created. Today's applications are based on this foundation.

1.2 What Is Process Control?

The best way to describe process control is through an example. Consider a simple situation: keeping a room at a comfortable temperature using a manually controlled heater. When the temperature of the room is too low, we turn the heater on until the temperature

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2 Basic Control Concepts

This chapter introduces fundamental concepts and terminology encountered in automated process control, namely, the concept of the control loop.

Learning Objectives

- Define the following terms:
  - Controlled (process) variable
  - Set point
  - Disturbances
  - Manipulated variable
- Understand the basic concept of feedback control
- Understand the basic concept of a control loop
- Have a general overview of process automation

2.1 Process and Process Control

Process as used in the terms *process control* and *process industry* refers to the methods of changing or refining raw materials to create end products. The raw materials, which either pass through or remain in a liquid, gaseous, or slurry (a mix of solids and liquids) state during the process, are transformed, transferred, measured, mixed, heated or cooled, filtered, stored, or handled in some way to produce an intermediate or end

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product. Process industries include the chemical, oil and gas, food and beverage, pharmaceutical, water treatment, and power industries, among others.

Process control refers to the methods used to control process variables when manufacturing a product. For example, factors such as the proportion of one ingredient to another, the temperature of the materials, how well the ingredients are mixed, and the pressure under which the materials are held all can significantly impact the quality of a product. Manufacturers control the production processes for three main reasons, to:

1. Reduce variability
2. Increase efficiency
3. Ensure safety

Reduce Variability

Process control can reduce variability in a product to ensure a consistently high-quality product. Manufacturers can also reduce cost by reducing variability. For example, in a gasoline blending process, 12 or more different components may be blended to make a specific grade of gasoline. If the refinery does not have precise control over the flow of the separate components, the gasoline may get too much of the high-octane components. As a result, customers would receive a higher grade and more expensive gasoline than they paid for, and the refinery would lose money. The opposite situation would be customers receiving a lower grade at a higher price.

Reducing variability can also lower cost by reducing the need for activities such as product padding to meet required product specifications. *Padding* refers to the method of making a product higher quality than it must be to meet specifications. When there is variability in the product (i.e., when process control is poor), manufacturers are forced to pad the product to ensure that specifications are met, which adds to the cost. With accurate, dependable process control, the *set point* (desired or most favorable point) can be moved closer to the actual product specification and thus reduce manufacturing cost.

Increase Efficiency

Some processes must be maintained at a specific point to maximize efficiency. For example, a control point might be the temperature at which a chemical reaction takes place. Accurate temperature control ensures process effectiveness and efficiency. Manufacturers save money by minimizing the resources required to produce the product.



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3 The Control Loop

The concept of a feedback control loop was presented in Chapter 2. This chapter expands on this concept by examining the functioning layout of a typical feedback control loop.

Learning Objectives

- Understand the functional layout for a typical feedback control loop
- Understand process control terminology
- Explain the components of a feedback control loop in terms of a block diagram

3.1 A Typical Feedback Control Loop

Any given process may have more than one controlled variable (CV), and for each controlled variable an associated manipulated variable. In practice, a specific controlled variable is paired to a specific manipulated variable through appropriate feedback control hardware. This is illustrated in Figure 3-1.

The CV is measured with appropriate instrumentation, such as a sensor and its associated electronics. This measured value of the controlled variable is then transmitted to the controller and compared to the desired value of the controlled variable (the set point). The difference between these two (the error) is used to produce the control action required by the manipulator, which in this example is the valve.

Based on the error or deviation, the controller calculates an output signal to adjust the manipulated variable. Usually, the manipulated variable is flow, and the output of the

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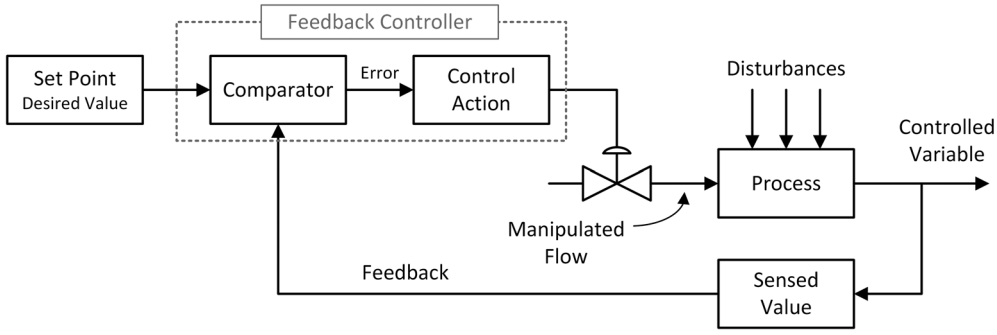


Figure 3-1. A single feedback control loop.

feedback controller is a signal to a control valve, as illustrated in Figure 3-1. While all this is happening in a continuous fashion, disturbances may enter the process and tend to drive the controlled variable in one direction or another. The single manipulated variable is used to compensate for all such changes produced by the various disturbances. In addition, if there are changes in the set point, the manipulated variable is also changed accordingly to produce the needed change in the controlled variable.

In a functional sense, all feedback control loops operate as illustrated in Figure 3-1.

3.2 The Three Tasks

The control loop performs three specific functions

1. measurement,
2. comparison, and
3. adjustment or manipulation.

Figure 3-2a shows a typical level control system. A level measuring device referred to as a *level transmitter* (LT1) measures the level in a tank and transmits the measured value (MV) associated with the level reading to a level controller (LC1). The controller compares the measured value to a desired set point (SP), in this case, a level established by the plant operator. In the meantime, there is a demand, adjusted by the hand valve (LV2) that removes liquid from the tank. This is detected by LT1, and then the controller sends a signal to the proportional control valve (LV1) bringing the level back to its required level. Note that all three devices—LT1, LC1, and LV1—have the first letter *L*, indicating they are part of the single level control loop as specified by ISA-5.1.[1]

1. ANSI/ISA-5.1, *Graphic Symbols for Process Measurement and Control* (Research Triangle Park, NC: ISA [International Society of Automation]).

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4 Functional Structure of Feedback Control

This chapter further develops the concept of block diagrams and introduces the concept of transfer functions to describe and analyze the functional structure of an automated process control loop. Combining transfer functions with block diagrams provides a powerful tool and method for simplifying and analyzing complex systems.

Learning Objectives

- Understand the functional layout for a single feedback control loop
- Explain the components of block diagrams
- Understand the meaning of a transfer function
- Draw and analyze block diagrams
- Appreciate the mathematical arrangement of a single feedback control loop
- Perform simple block diagram reduction and analysis

4.1 The Transfer Function

A transfer function is a mathematical representation of a component, system, or process. Specifically, it is the ratio of the output divided by the input of the component, system, or process. Usually, transfer functions are represented with capital letters; popular letters are *H*, *G*, and *K*.

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Mathematically, a transfer function can be represented as:

$$transfer\ function = TF = \frac{output}{input} \tag{4-1}$$

This can also be represented graphically in block diagram form as follows:



Because the transfer function is a ratio, its dimension is the output units divided by its input units. When both are of the same dimension, the transfer function is dimensionless. In process control, all elements and instruments can be expressed using transfer functions. Complex transfer functions are usually expressed in functions that describe an element or instrument's dynamic behavior. *Dynamic* means how the output changes relative to the input. The block represents the change that the input undergoes to produce an output. This means the output is equal to the input multiplied by the block transfer function.

$$output = TF \times input \tag{4-2}$$

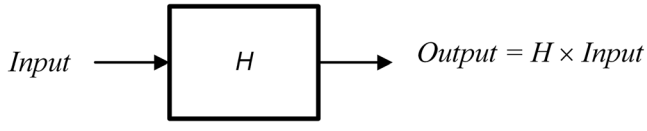
4.2 Block Diagrams

Block diagrams provide a consistent way of representing control systems pictorially. It is useful to take advantage of block diagrams because they are simple, symbolic, graphical tools commonly used in automatic control. Block diagrams have three basic symbols:

1. Block
2. Summing junction
3. Takeoff point

The Block

The block represents the transfer function of the system element.



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5 Dynamics of Systems

The term *dynamics* refers to how a system's output changes when the input changes or how a system reacts to a change in set point, load, or disturbances. Dynamics is often referred to as *transient*, meaning the temporary change in how a process reaches a new steady state. It is important for the automation professional to develop an overall understanding and appreciation of dynamic behavior of the process, its element, and the process control loop. This chapter describes many of the general concepts and principles of dynamics and its associated terminology.

Learning Objectives

- Know the general response characteristics of a first-order lag component that has been subjected to a step input
- Determine graphically the time constant for a first-order lag system that has been driven by a step input
- Distinguish the difference between real dead time and apparent dead time
- Identify and quantify the dead time on a process response curve
- Understand the effects of process lags and dead times on loop process dynamics
- Understand and determine process gain and sensitivity

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5.1 Dynamic Components

Dynamics describes how a component or system responds to change over time. The various elements represented by blocks of a feedback control loop have different types of dynamic behavior, and it is important that you gain insight into these process dynamics.

Every change in input will produce a corresponding change in output.

Many of the individual components of the process control loop have no significant time-dependent behavior, that is, there is neither lag nor lead in their operation. When the input to a component changes, the output of the component changes instantaneously, for all practical purposes.

This type of component, illustrated in Figure 5-1, is referred to as a *nondynamic* component. In effect, it can be described as a pure gain. For all practical purposes, the output changes instantaneously when the input changes. The output is always directly proportional to the input, and this proportionality constant is referred to as the *gain K* of the component. The term *gain* does not necessarily imply that the output is greater than the input. *Gain* is also used when the output is smaller than the input. When this occurs, it is called *attenuation*. In that case, K will be less than one ($K < 1$).

Components that do not exhibit dynamic behavior are referred to as *zero-order systems*.

Many components do exhibit dynamic behavior. Typically, their output lags or leads any input or alters the input significantly; lag tends to be far more common than lead. When such time-dependent behavior is encountered, it can appear as shown in Figure 5-2. Systems and components that exhibit such dynamic behavior are referred to as *first-order* or *second-order* systems, or *higher-order* systems. The order refers to the number of elements capable of storing material or energy within the system.

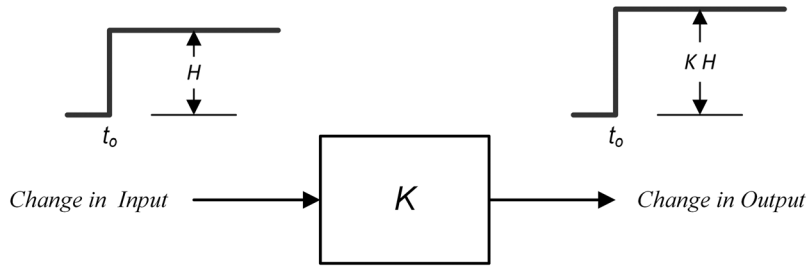


Figure 5-1. Nondynamic behavior of a component.

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6 Process Characteristics

The characteristics of a process are an expression of the relationship between the manipulated variable (process input) and the controlled variable (process output).

Understanding the characteristics of a process enables proper analysis, modeling, and tuning of the process.

Learning Objectives

- Understand the general response characteristics of typical processes
- Determine the characteristics of the following types of processes:
  - Integral
  - Self-regulating (first-order lag)
  - Second-order lag (resonance and damping ratio)
- Derive the time-domain and process transfer function equation

6.1 Introduction

One of the most important aspects of controlling a process is to know and understand the process. Adequately understanding the characteristics of a process will provide valuable information in controlling it. We will next investigate different process characteristics and how to identify each.

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To design, analyze, or simulate a process, we must understand how the process works and be able to clearly model the process mathematically. By developing mathematical models of processes, we can simulate their responses and clearly determine their characteristic response. Process and system modeling will be covered in detail in Chapter 18. This chapter will outline fundamental characteristics of some of the basic processes.

There are three major classifications of process response:

1. Integrating
2. Self-regulating
3. Runaway

Each of these process types can be defined by its response to a step change in input or the manipulated variable.

An integrating process responds by ramping either up or down at a rate proportional to the magnitude of the final control element's step change.

A self-regulating process responds to a step change in the final control element's status by settling to a new stable value.

A runaway process responds by ramping either up or down at a rate that increases over time, headed toward complete instability without some form of corrective action from the controller. Runaway processes will be discussed in Chapter 18.

The characteristics of a process are an expression of the relationship between the manipulated variable (input) and the controlled variable (output). In other words, the process or plant can be expressed as a transfer function and is referred to as the *process* or *plant transfer function*. System modeling is primarily based on determining mathematical relationships of the process.

Most control components and systems can be classified by means of determining their characteristic response to a step input. The following five classifications are prominent:

1. Integral
2. First-order lag



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7 Sensors, Transducers, and Transmitters

For process control to function, you must be able to measure the process variable. The performance quality of a feedback control system is directly dependent on the validity of the process variable measurement. This measured value must be transmitted to the controller in a timely fashion so that corrective action may be calculated and transmitted to the final control element. This chapter provides a brief study of some of the more common devices used in measuring process variables and the operation of these measuring and transmission elements.

Learning Objectives

- Understand the difference between a sensor, a transducer, and a transmitter
- Understand more fully the role and functioning of the sensors in a feedback control loop
- Define *accuracy*, *precision*, and *sensitivity*
- Understand the 4 to 20 mA current loop

7.1 The Sensor, Transducer, and Transmitter

One critical problem in designing and installing a feedback control loop is specifying the measuring system that will obtain a measurement of the controlled variable. The measuring element not only provides a measurement of the process variable, but it

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also provides the feedback that causes the change of the process variable by means of the feedback control loop. The change of variable takes place because the process variable itself is not the actual signal that is transmitted back to the comparator. The transmitter produces an output signal whose steady-state value has a predetermined relationship to the controlled variable. A transmitter is not required from the standpoint of either measurement or control. The transmitter is an operating device that forwards the measured value of the controlled variable to a more convenient and/or a more centralized location, for example, in a remote control room. The transmitter output signal is generally in a standardized form, such as 3 to 15 psig air pressure or 4 to 20 mA DC. From a hardware standpoint, the measurement function and the transmitter function are often both incorporated into a single device.

Some of the most common process variables are temperature, pressure, flow, composition, liquid level, speed, and position. Some of these variables, such as pressure, can be measured relatively directly, while others, such as temperature, can only be measured indirectly.

There is no consensus as to what distinguishes a sensor from a transducer. For this book, we will make the following distinction: an *electrical sensor* is a device that converts an energy form directly to an electrical output signal. Typical examples are thermocouples, resistors, and capacitors. An *electrical transducer* is a device composed of a sensor, whose output is modified or conditioned to suit a specific application. The transducer receives information in one physical form, modifies the information or its form, or both, and sends an electrical output signal. Depending on the application involved, a transducer in a functional sense can be a primary measuring element (a sensor), a transmitter, a relay, a converter, or some other device. Many of these terms—*sensor*, *transducer*, *converter*, and *transmitter*—have broad and sometimes overlapping meanings, and quite often the installation of a piece of hardware will dictate the appropriate descriptive term. Confusion can be minimized if the practitioner focuses on the function involved rather than the term. To summarize:

- *Sensors* are devices that detect variables, such as pressure, temperature, movement, electrical signals, radiant energy, and thermal or magnetic energy, and provide mechanical or electrical outputs that are directly related to the magnitude of the variables.
- *Transducers* are devices that can change one form of energy to another. For example, a resistance thermometer converts temperature into electrical resistance. The term *transducer* applies most often in control loops to such instruments that convert an electrical signal to a pneumatic signal or a pneumatic signal to an electric signal.



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8 Actuators and Final Control Elements

Actuators are mechanical, electromechanical, pneumatic, and hydraulic devices that provide linear or rotational movement to position the final control element.

The *final control element* is that portion of the control loop that directly changes the value of the manipulated variable.

Learning Objectives

- Be familiar with the different types of actuators
- Be able to differentiate the actuator from final control element
- Understand the purpose and use of control valves, valve actuators, and valve positioners
- Be able to define rangeability and turndown ratio
- Know the meaning and use of valve coefficients and appreciate sizing considerations

8.1 Introduction

In previous chapters, we introduced the concept of the process control loop, and defined its three elements: measurement, comparison, and adjustment or manipulation. The

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final control element is perhaps the most important because it exerts a direct influence on the process. Final control elements contain the essential pieces of equipment to convert the control signal, generated by the process controller, into the action required to correctly manipulate the process to meet its desired value.

In this chapter, we will cover some of the fundamental principles of final control elements and actuators, such as control valves, motors, pumps, and solenoids. Because control valves are the single most common type of final control element in process control, we will discuss them first and in greatest detail. However, it should be understood that there is no attempt made here to be anything but a cursory overview of actuators and final control elements.

8.2 Control Valves and Actuators

In the vast majority of process control applications, the final control element is a valve. A control valve is in essence a device that regulates the flow of a process fluid. In a control valve, an actuator is connected to the valve's plug stem to move the valve between the open and closed positions to regulate flow. The valve body is mounted in the process fluid line and is used to control the flow of fluid in the process.

These valves are usually driven by pneumatic, solenoid or motor actuators. An example of a typical control valve and actuator is illustrated in Figure 8-1. This is a sliding-stem, single-seat control valve body with a pneumatic actuator.

There are essentially two types of control valves:

1. Linear-motion control valves that commonly have globe, gate, diaphragm, or pinch-type closures
2. Rotary-motion valves that have ball, butterfly, or plug closures

Each type of valve has its special generic features, which may, in a given application, be either an advantage or a disadvantage.

The control valve actuator is used to translate the specific output signal from the controller into a mechanical movement that drives the stem of the control valve. Control valve actuators may be pneumatic, electric, hydraulic, or manual. The most commonly used valve actuators in the process industries are pneumatic, and most of these have a diaphragm to move the stem. The diaphragm is spring loaded in opposition to the driving air pressure so that the valve stem position is proportional to air pressure.



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9 Controllers

The controller is the element of the process control loop that processes information needed to perform the decision-making function. The controller can be considered the brain that enables automated systems to operate without human intervention.

The feedback controller determines the changes that are needed in the manipulated variable to compensate for disturbances that upset the process or for changes in the set point (SP). A clear understanding of the computational aspect of the controller is necessary for proper use and tuning of the process control loop.

Learning Objectives

- Understand the computational ability of a proportional-integral-derivative (PID) controller
- Explain proportional control action and its advantages and disadvantages
- Explain integral (reset) action and its advantages and disadvantages
- Explain derivative (rate) control action and its advantages and disadvantages

9.1 The PID Controller

Most process control is done using a PID controller. This is a special-purpose computer that uses the set point (SP) and measured value (MV) of the process as its input or forcing function, and calculates the changes needed in the manipulated variable to maintain the controlled variable at its desired set point despite changes in set point, load changes, or disturbances.

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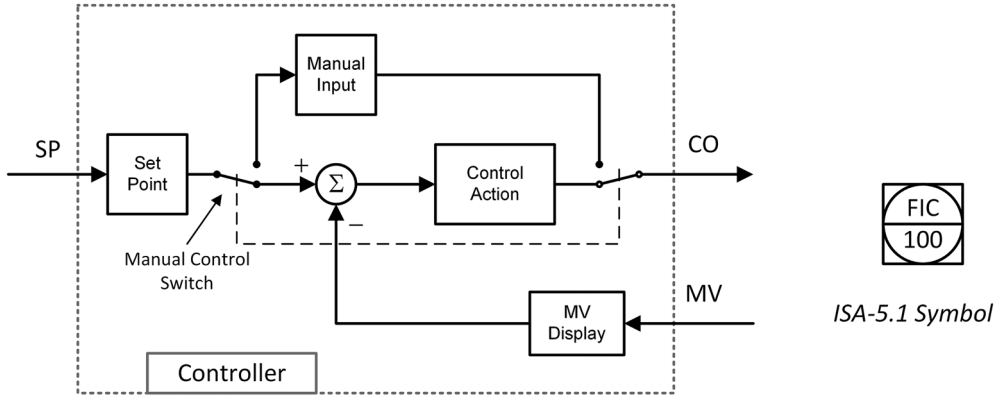


Figure 9-1. Block diagram and ISA symbol of a typical controller.

A PID controller is essentially a device or instrument that maintains a feedback control loop at its desired set point, whether that is the temperature in a room, a quadcopter, or the pressure in a vessel. Most (over 90%) controllers in industry are PID controllers.

Figure 9-1 is a simplified block diagram of a typical PID controller. The controller is symbolized using ISA-5.1[1] symbols as indicated.

The input applied to the controller is the MV and the required SP. The controller first calculates the error signal, which is the difference between the SP and the MV, which is the feedback signal. The controller then calculates the change needed in the controlled variable to compensate for disturbances that upset the process or changes in the SP. The controller responds to these changes by producing a controller output (CO) signal that drives the actuator to alter the process variable until the error signal is reduced to zero.

The controller may be as simple as a mechanical lever like the one in a common toilet tank as we saw in Chapter 1; or as complicated as a computer, a programmable logic controller (PLC) or a programmable automation controller (PAC). It may control one process or several simultaneously. The controller may be analog, digital, or pneumatic, or a combination of all three.

Most process controllers are designed as general-purpose industrial process controllers, although some have inputs that can be connected directly to thermocouples or

1. ANSI/ISA-5.1-2009, *Instrumentation Symbols and Identification* (Research Triangle Park, NC: ISA [International Society of Automation]).

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10 Tuning Control Loops

A feedback control loop is of little value if it is improperly tuned. A properly tuned control loop maintains its process value at its desired set point, regardless of external disturbances. Chapter 9 explained the different control modes available on most proportional-integral-derivative (PID) controllers. This chapter will explain how to adjust them.

Tuning a feedback control loop involves setting the proportional, integral, and derivative values to get the best possible control for a specific process control loop. Controller tuning is at best an educated trial-and-error process that requires experience more than anything.

It is important that you understand how the controller in a feedback control system should be tuned.

Learning Objectives

- Develop a fundamental understanding of tuning a feedback controller
- Calculate the tuning parameters for a process control loop using the Ziegler-Nichols ultimate method
- Calculate the tuning parameters for a process control loop using the process reaction curve method

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10.1 Know Your Controller

An important aspect of tuning a process control loop is to understand exactly what type of controller you are using, what it is doing, and how it is doing it. Controllers come in many different flavors. Make sure to read the manual for the controller you are using. All PID controllers are tuned by adjusting the following three parameters:

1. K_C – Controller gain (or proportional band)
2. T_I – Reset rate (or integral gain)
3. T_D – Derivative time

How to adjust these tuning parameters on a feedback control loop is one of the least understood and most poorly practiced aspects of process control, yet it is very important.

Proportional

The proportional gain adjustment (K_P) on many PID controllers is not expressed in terms of proportional gain, but in terms of proportional band (PB). PB is defined as the span of values of the input that corresponds to a full or complete change in controller output. This is usually expressed as a percentage. Note that proportional gain is equal to controller gain (K_C). K_C is related to K_P and PB by the following equations:

$$K_P = K_C$$
$$PB = \frac{1}{K_P} \times 100\% \tag{10-1}$$

The larger the PB, the greater the area around the set point in which the proportional action takes place. Note that although PB and K_P are the same, proportional gain does not directly provide information about the controller's actual range as does PB.

Because most controllers have a scale that indicates the value of the final controlled variable, the PB can be conveniently expressed as the range of values of the controlled variable that corresponds to the full operating range of the final control element. This full operating range of the final control element is often inferred to be the operation of a final control valve through a full stroke.

Integral

Integral gain, also known as *reset*, is a function that adjusts the proportional band-width with respect to the set point to compensate for offset from the set point; that is, it

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Section 2

Control Strategies

This section (Chapters 11 through 17) discusses different control strategies.

Control strategy refers to a plan or methods applicable to a specific control requirement that cannot be satisfied using a simple control loop. It usually consists of combining multiple control loops to realize specific control outcomes, or applying a nontraditional approach in combination with a standard process control loop.

Chapter 11 addresses cascade control. Cascade control involves the use of two controllers with the output of the first controller providing the set point for the second controller. This form of control is used to improve responses to disturbances.

Chapter 12 focuses on feedforward control. Feedforward control applies corrective action by measuring disturbances and anticipating corrective action before the disturbance enters the process. It is usually applied in conjunction with feedback control.

Chapter 13, "Multivariable Control," explains the process for controlling two or more interdependent process variables.

Chapter 14 explains how ratio control is used to maintain a constant flow rate of two or more streams in a process at a specified proportion relative to one another.

Chapter 15 discusses special control strategies such as three-element boiler control, selective control, override control, duplex and split-range control, and auto-selector or cutback control.

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Chapter 16, "Statistical Process Control|," explains the application of statistics to process control. This type of control applies statistical methodology to measure and control product quality in real time during the manufacturing process.

Chapter 17, "Fuzzy Logic Control," provides an introduction to applying set theory and fuzzy logic to process control problems.

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11 Cascade Control

Up to this point, whenever feedback control was discussed, attention was focused on a single feedback control loop. This chapter will expand that concept to several variations of this single-loop approach to include a secondary control loop using the principle of cascade control.

Learning Objectives

- Recognize the basic principle of cascade control
- Understand the basic concepts that govern the selection of a secondary controlled variable
- Understand the general guiding principles for cascade control mode selection and tuning

11.1 The Concept of Cascade Control

Cascade control enables the reduction of disturbances that are external to the process. The process variable, which is to be maintained at a fixed set point, is called the *primary variable*. A secondary variable that may introduce disturbances to the primary variable is identified. The output of the primary controller is then used as the set point of the secondary controller.

For example, in a home heating system (Figure 11-1), room temperature is maintained by controlling the amount of fuel to a furnace. The temperature transmitter (TT 100) reacts to disturbances in the room, and the controller calculates the required change

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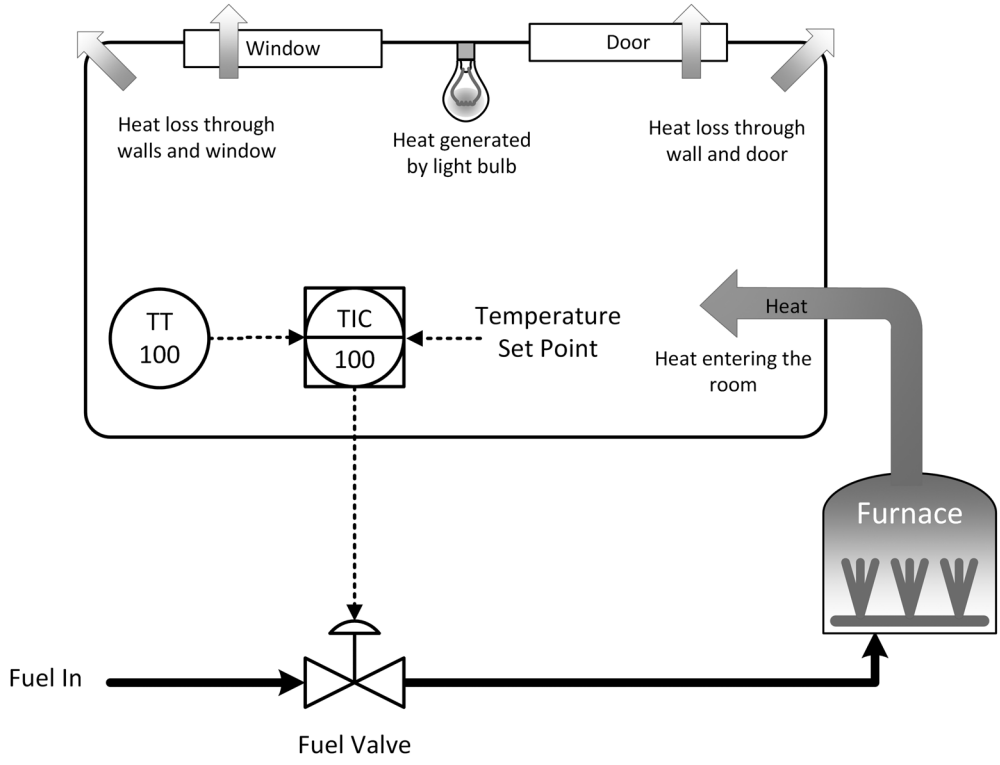


Figure 11-1. Feedback control of a home heating system.

needed to the fuel valve to maintain the desired room temperature. However, the fuel line supplying the fuel may also add disturbances, such as variations in fuel supply pressure, which in turn changes the amount of fuel supplied to the furnace. The temperature controller only responds to temperature changes measured by TT 100. It is not able to respond to fluctuations in fuel pressures because the time lag and dead time of this type of disturbance with respect to temperature is much larger than the fluctuations in fuel pressure. The temperature controller, not the valve opening, must determine the required fuel flow rate. This means we must also control the fuel flow rate.

The fuel flow rate can be controlled by using cascade control. A cascade control system consists of a primary (outer) control loop and a secondary (inner) control loop. In the home heating system example, the primary control loop is room temperature, and the secondary control loop is the fuel flow rate. Figure 11-2 illustrates how cascade control implements this arrangement.

The temperature controller (TT 100) controls the temperature not by controlling the valve opening, but rather by controlling the actual fuel flow rate to the furnace. The flow controller (FC 101) in turn controls the fuel valve and maintains the fuel flow as directed by the temperature controller. This arrangement will minimize any

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12 Feedforward Control

Most control theory that was covered in Section 1 focused on feedback control. This chapter describes some of the inadequacies of feedback control and shows how feedforward control can be used when applicable. Feedforward control is based on the premise that the system designer has a clear understanding of the disturbances involved in the process, is able to quantify them, and then takes preemptive action to prevent the disturbances from affecting the process variable. Feedforward control could be useful in some cases even if the designer does not have a clear understanding of the disturbances. This will be illustrated using our home heating system example.

Learning Objectives

- Understand the fundamental concepts of feedforward control
- Define the structure of the control action equation contained in a feedforward controller
- Understand how feedforward control is used in practice, especially in combination with feedback control

12.1 Feedforward Control

Feedforward control is different in concept from feedback control. A manual implementation of feedforward control is illustrated in Figure 12-1.

In this control strategy, as a disturbance enters the process, the operator observes the disturbance and, based on the nature and quantity of the entering disturbance,

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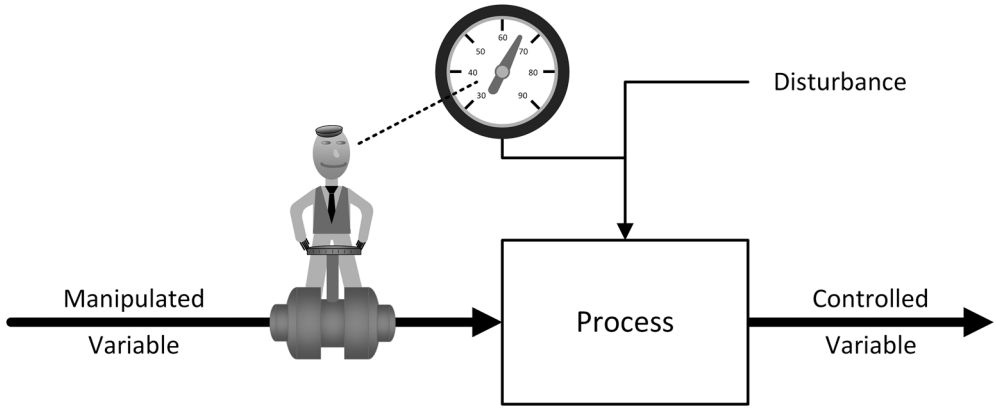


Figure 12-1. Manual feedforward control.

adjusts the manipulated variable in such a manner as to prevent any eventual change or variation in the controlled variable due to the observed disturbance. The conceptual improvement is obvious. Feedback control works to eliminate errors; feedforward control operates to prevent errors from occurring in the first place.

For example, in a home heating system (Figure 12-2), room temperature is maintained by controlling the amount of fuel to the furnace. The temperature transmitter (TT 100)

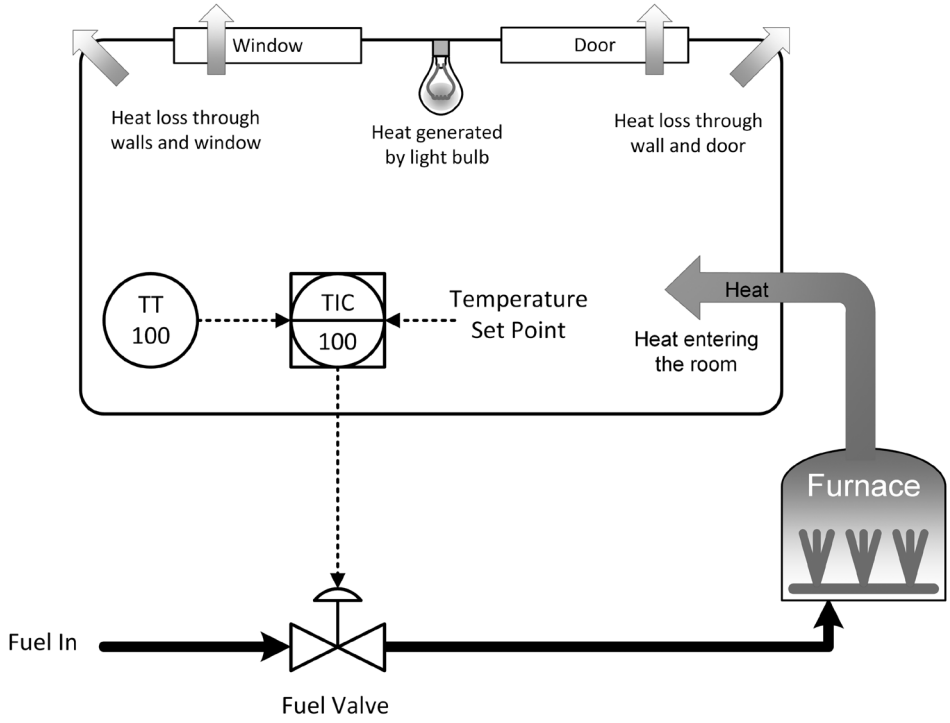


Figure 12-2. Control of home heating system.

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13 Multivariable Control

In previous chapters, we viewed the control system as primarily having one or more independent control loops. In practice, there are processes in which different control loops interact with each other. Multivariable control is a method of dealing with multiple interacting control loops.

Learning Objectives

- Understand the concept of multivariable control
- Understand the problems associated with multivariable control
- Articulate possible multivariable control solutions

13.1 The Multivariable Control Concept

Consider, for example, a temperature control loop and a humidity control loop for a typical home. Decreasing the temperature will also decrease the relative humidity. Raising the humidity will raise the temperature. The required balance of comfort is difficult to resolve. In other words, one control loop affects the other.

The two control loops in Figure 13-1 illustrate the loop interaction. This represents what is called a 2×2 *process* (two controlled variables and two manipulated variables).

When there are two control loops on one unit, often the two control units will interact with one another. Specifically, when there is a change in the manipulated variable in Loop 1, not only will it produce a change in the controlled variable for Loop 1, but it will also produce a change in the controlled variable for Loop 2. Conversely, when

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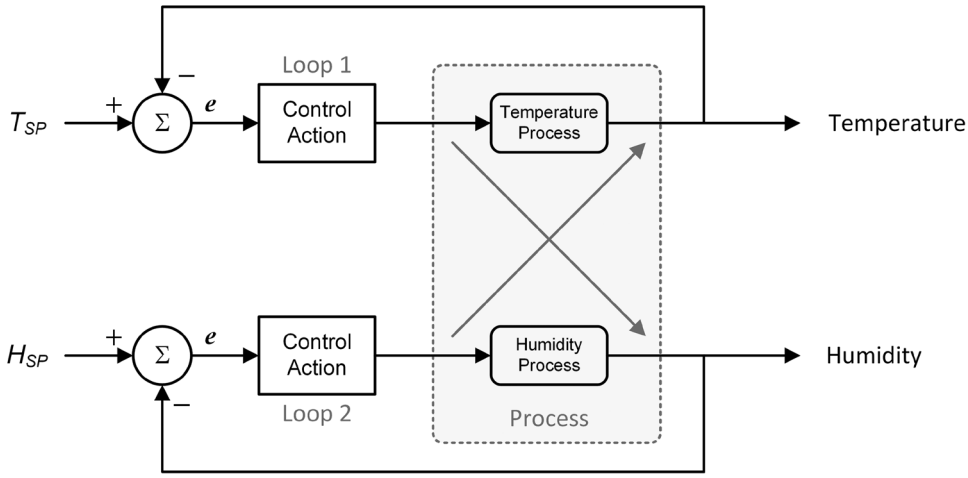


Figure 13-1. Conventional multivariable arrangement.

there is a change in the manipulated variable for Loop 2, it will produce a change in the controlled variable for Loop 2 but also in the controlled variable for Loop 1. This type of control interaction can produce significant control problems. When a change in the manipulated variable for Loop 1 occurs, there will be a change in the controlled variable for Loop 1. However, in addition, the change in the manipulated variable for Loop 1 will produce a change in the controlled variable for Loop 2. This, of course, will be sensed and fed around Loop 2, and will, in turn, produce a change in the manipulated variable for Loop 2. This not only produces the change in the controlled variable for Loop 2 but also produces a further change in the controlled variable for Loop 1. In effect, these loops start to chase one another in a figure-eight type of path as shown in Figure 13-2. To compensate for this, the control system must desensitize the loops, making it more complex and difficult to obtain quality feedback control.

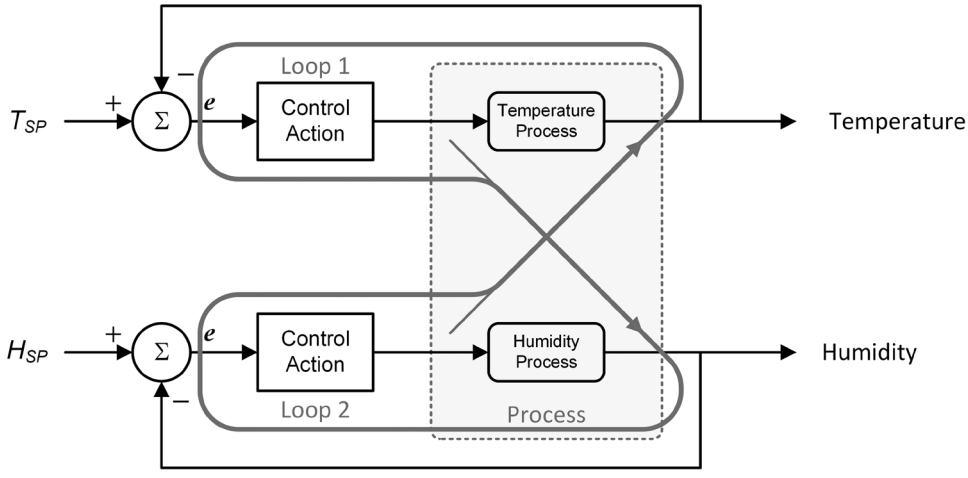


Figure 13-2. The effects of interaction in a 2 × 2 system.

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14 Ratio Control

A commonly encountered type of multiple-loop feedback control system is *ratio control* (also called *fraction control*). Ratio control is used to ensure that two or more process variables are kept at a fixed ratio to each other, even though they are changing in value.

In industrial control systems, ratio control is used in maintaining the burner air/fuel ratio, in the mixing and blending of two liquids, in injecting modifiers such as pigments into resins before molding or extrusion, and in adjusting heat input in proportion to material flow.

Learning Objectives

- Recognize basic ratio control
- Understand the basic principles of ratio control
- Distinguish how and when to apply ratio control

14.1 The Ratio Control Concept

Ratio control is often confused with cascade control; however, the function of ratio control is quite different from that of cascade control. Ratio control resembles feedforward control but is, in effect, a special type of feedforward control. In ratio control, one loop adjusts a second control loop, and the second control loop is fractionally controlled by the first control loop in a feedforward manner, with their ratio maintained at a set fraction. Ratio control is often associated with process operations in which two or more streams must be mixed together continuously to maintain a steady composition in the resulting mixture, such as the air-to-fuel ratio (AFR) of an industrial combustion chamber.

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In ratio control, we measure the flow of the first stream (referred to as *wild flow*) and then calculate (based on the required ratio) the value of the second stream (referred to as the *controlled flow*). A practical way to do this is to control one stream with a conventional flow controller and control the other stream with a ratio controller that maintains that stream flow at some preset ratio or fraction to the primary stream flow. Ratio control is then a form of feedforward control of the second steam. This is also referred to as a *wild feedforward loop*. You measure the disturbance of the first flow and calculate the ratio required for the second flow. This type of control is commonly referred to as a *multiple-loop feedback control system*.

This concept is best illustrated using the example of a home heating system. The furnace not only needs its fuel intake controlled to provide proper heating, but it also requires a proportional amount of air for efficient combustion, referred to as the *stoichiometric air-to-fuel ratio*.[1] Assuming the amount of fuel flow to the furnace is A and the amount of air required is B, the ratio of air to fuel can be expressed as $R = B / A$. Figure 14-1 shows that the fuel to the burner is measured using FT 102 and is then

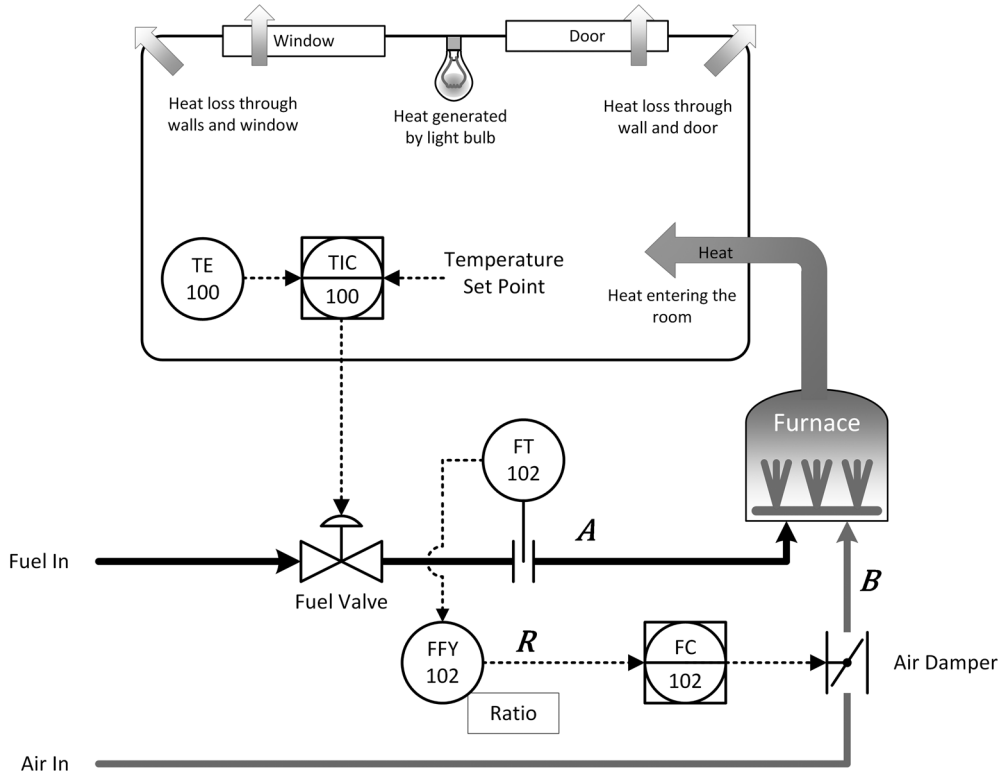


Figure 14-1. Home heating system showing ratio control of fuel and air.

1. For natural gas, the air-to-fuel ratio is approximately 10.

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15 Special Control Strategies

There are many important variations, extensions, and modifications of the standard control strategies. To illustrate the diversity of possible principles and concepts, this chapter will present several such implementations.

Learning Objectives

- Understand three-element boiler control
- Understand selective control
- Understand override control
- Recognize duplex and split-range control
- Recognize auto-selector or cutback control

15.1 Introduction

As we employ more advanced control strategies, the number of computational requirements increases. These additional computational functions are usually implemented by either specialty controllers or general-purpose controllers, with programmable functions primarily implemented by microprocessors. However, as we consider various control strategies, it is helpful to also consider the signal processing functions that are involved and the specific functions of the various computational operations.

The use of microprocessors extends this list virtually without limit. Complex calculations can be done without an increase in hardware. However, the increase in software

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development can be complex and expensive to implement and maintain. Previous chapters discussed the use of specialty controllers, such as in feedforward control (Chapter 12) and in multivariable control (Chapter 13). Special signal processing functions have also been introduced in ratio control (Chapter 14). Advanced process control functions are now standard in most programmable logic controllers (PLCs), programmable automation controllers (PACs), and distributed control systems (DCSs). Typical computational components used in process control include the following:

- **Addition/subtraction** – The output signal is the algebraic sum or difference of the input signals.
- **Multiplication/division** – The output signal is produced by multiplying or dividing the input signals.
- **Square root extraction** – The output signal is the square root of the input signal.
- **High/low selector** – The output signal is the highest/lowest of two or more input signals.
- **High/low limiter** – The output signal is the input signal limited to some preset high/low value.
- **Function generator** – The output signal is a function of the input signal.
- **Integrator** – The output signal is the time integral of the input signal. An integrator is also often called a *totalizer*.
- **Linear lag** – The output signal is the solution of a first-order differential equation in which the input signal is the forcing function. This is expressed mathematically as follows:

$$output = \left(\frac{K}{1+\tau s}\right) input \tag{15-1}$$

where

K = gain
τ = time constant
s = Laplace transform operator d/dt

- **Lead-lag** – The output signal is the solution to the following differential equation. This is expressed mathematically as follows:

$$output = K\left(\frac{1+\tau_1 s}{1+\tau_2 s}\right) input \tag{15-2}$$



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16 Statistical Process Control

Statistical process control (SPC) refers to using statistical methods to measure process quality, consistency, and variations in an effort to produce a higher quality product and reduce product rejects. SPC is a primary tool to improve product quality by reducing process variation. It is most often used when a large number of items, such as prepared food and pharmaceutical products, are produced.

The focal point of SPC is its ability to provide a continuous quality-improvement tool kit. SPC can be used as the primary tool for monitoring, control, and diagnostics.

Learning Objectives

- State the basic approach of statistical process control (SPC) and the tools used therein
- Understand the purpose of SPC
- Interpret control charts and variability
- Explain the meaning of the following terms:
  - Sample and population
  - Mean or average
  - Variability and range
  - Standard deviation

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16.1 Introduction

SPC, in addition to other control strategies, is often used to monitor the consistency of processes used to manufacture a product as it is designed and specified. Its aim is to maintain and keep processes under control despite variability in the materials, methods, machines, personnel, and environment used in the production of the product. No matter how good or bad the design, variability is inevitable. SPC helps to ensure that the product is being manufactured as designed and specified. SPC will not improve a poorly designed product's reliability or quality, but it can be used to assist and maintain a consistency in the manufacture of a product.

16.2 Statistics (Mean and Standard Deviation)

Statistics is the knowledge and science of variation, and for that reason it is an excellent tool to monitor and control variations.

Statistics requires collecting data. The problem is that after the data is collected, what do we do with it? Statistical techniques help us visualize massive amounts of data and, with proper analysis, make the data useful in maintaining product quality. To fully understand a process and its variability, and the effect of changes in process variables, rules of thumb and experienced people are valuable. However, significant decisions should be based on properly collected and analyzed data.

We start by reviewing some fundamental concepts and terminology. In dealing with statistics, we distinguish between the *sample* data and the *population* that the sample data represents. We use the sample data to draw conclusions about the population. In dealing with SPC and improving quality, it is more natural to speak of processes than populations.

- **Sample** – Refers to a collection of data that has actually occurred; a set of existing measurements that have been recorded in some way, usually electronically. The term *population* is used in statistics to refer to all possible samples that could have been collected. In manufacturing and in SPC, we usually draw conclusions based on the sample rather than the population.
- **Distribution** – A summary of the sample (the data points collected) that is usually presented in the form of a histogram.
- **Range** – The difference between the largest and smallest values of a sample.
- **Mean** – The mean, or average, is a measure of location of the distribution. This is one of several statistical parameters that describe the sample. The



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17 Fuzzy Logic Control

Fuzzy logic control is a relatively new concept in process control and is particularly useful when systems are difficult to model mathematically.

Learning Objectives

- Understand the basic concepts of fuzzy logic control
- Explain the meaning of the following terms:
  - Rule-based
  - Fuzzification, defuzzification
  - Membership function
- Explain and delineate the membership functions

17.1 Origin of Fuzzy Logic

The concept of fuzzy logic was originally conceived by Lotfi Zadeh, a professor at the University of California at Berkley, and presented not as a control methodology but as a way of processing data by enabling partial set membership rather than crisp set membership or nonmembership. This means that adjectives such as *hot* or *cold* are not exact (or not crisp), but rather they depend on one's perception. This approach to set theory was not applied to control systems until the 1970s. Professor Zadeh reasoned that people do not require precise, numerical information (input), and yet they are highly capable of adaptive control functions (output). A perfect example of this is

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driving a car, as we saw in Chapter 1. If feedback controllers could be programmed to accept noisy, imprecise input, they could be much more effective and perhaps easier to implement.

17.2 What Is Fuzzy Logic?

Fuzzy logic is a problem-solving control method that lends itself to implementation in systems ranging from simple, small, embedded microcontrollers such as room temperature controllers, to large, distributed networks of data acquisition and control systems. It can best be implemented in software or in a combination of both software and hardware. Fuzzy logic provides a simple way to arrive at a definitive conclusion based on vague, ambiguous, imprecise, noisy, or missing input information. In its simplest approach, fuzzy logic mimics how a person would make decisions.

Fuzzy logic offers several unique features that can make it a good choice for many control applications.

- Fuzzy logic is inherently robust, particularly in a noisy environment, because it does not require precise inputs and can be programmed to fail safely if a feedback sensor quits or is destroyed.
- Fuzzy logic is not limited to a single feedback input and control output. This makes fuzzy logic control a candidate in multivariable control applications. Any sensor data that provides some indication of a system's actions and reactions can be incorporated.
- Fuzzy logic can also be used to control nonlinear systems that are difficult or impossible to model mathematically.

17.3 Operating Rules

Fuzzy logic is based on rules such as IF x AND y THEN z. This approach to solving control problems mimics rational thinking and does not require an attempt to mathematically model the system to be automated. The fuzzy logic approach is empirically based, relying on experience rather than a detailed technical understanding of the system. For example, instead of dealing with temperature control in terms of set point and proportional-integral-derivative (PID) control, fuzzy logic deals with linguistic rules, taking the form of "IF THEN" statements. Each antecedent (condition) and each consequent (result) is determined by membership functions that are often geometrically represented by triangles or other shapes. The fuzzy logic controller deals with temperature as follows:



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Section 3

Advanced Topics

This section (Chapters 18 through 22) introduces advanced topics to encourage the reader/student toward further studies in process control.

The section starts by continuing and formalizing the discussion we started in Chapter 6, "Process Characteristics." Chapter 18, "Process Modeling and Simulation," provides an overview of process modeling and explains the science and mathematics behind the models. It also introduces the idea of simulating process control systems based on the models derived.

Chapter 19 discusses controlling dead time and the benefits of model-based control. By creating an accurate model of the process, a better controller for the process can be designed and processes with long dead time and/or interacting variables can be controlled more effectively.

To some extent, all real applications have nonlinear characteristics. The control system must either compensate for the nonlinearities or adapt to them. Chapter 20 discusses both nonlinear and adaptive control.

Chapter 21 provides a historical view of distributed control and control system architecture and how it has evolved. It also looks at the structure of large control systems and provides insight into their advantages and disadvantages.

Chapter 22 introduces digital systems, specifically digital signal processing, computer implementation of process models, and controller design. The chapter examines how computer computations, models, and simulations are implemented in a typical controller and/or computer.

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18 Process Modeling and Simulation

One of the most difficult aspects of designing an automated system is translating its connectional physical implementation into a set of equations that accurately describes the process.

Deriving models can be a complex topic, and in keeping with this book's philosophy, we will outline only some of the fundamental concepts.

Learning Objectives

- Understand the concept of developing a model based on the laws of science
- Develop the required differential equations and transfer functions
- Distinguish between static and dynamic models
- Distinguish between an experimental and a mathematical model
- Develop an appreciation of system simulation based on derived models

18.1 Introduction

Usually, it is impossible to describe a system completely. In the design process, every effort must be made to derive a set of equations that describes the physical system approximately and adequately, within its intended use and context.

We discussed the idea of modeling in Chapter 5, "Dynamics of Systems," and Chapter 6, "Process Characteristics." In Chapter 5, we used experimental measurements to

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derive a first-order plus dead time (FOPDT) model of a process; and in Chapter 6, we derived models of integral, self-regulating (first-order lag), and second-order lag processes from first principles. We also showed in Chapter 6 how the time-domain and frequency-domain points of view are related by the Laplace transform.

After we have derived a set of equations, we compare the data generated by the equations with data collected from the physical system by measurements, if possible. If the two sets of data agree or are sufficiently close within their intended use and context, we then gain confidence that the set of equations will lead to a good description of the real-world system. The equations can then be used to make predictions about the dynamic and static, long-term behavior of the system under different scenarios. It is important to keep in mind that the set of equations stays valid only as long as the two sets of data are close, and the intended use and context have not changed. If a prediction from the equations leads to some conclusions that are not close to the real-world behavior, then we should modify and correct the underlying equations. Generating good equations is not an easy exercise.

The set of equations, once derived, is referred to as a *model* of the system.

Dynamic versus Static

Process models can be classified as *dynamic* or *static* (meaning steady-state). In dynamic models, most variables are a function of time, and these models are used to predict how systems behave when subjected to changes in set points, load changes, or disturbances. Static models are often derived from their dynamic counterpart by setting the derivative terms to zero. which is referred to as the *final value property of the Laplace transform* (see Appendix C).

Static models describe the systems once a steady state has been reached and are most useful for design calculations,

Experimental versus Theoretical

Experimental models, as the name implies, are derived from tests performed on an actual process. These models tend to be simpler and easier to manipulate, and they are usually first- or second-order approximations of the theoretical model (see Chapter 5). Experimental models are an alternative to physics-based models and use input/output data to develop empirical dynamic and/or static models of systems.

Theoretical models are derived from the fundamental laws of physics and chemistry. They tend to be complex but provide a better understanding of the process (see Chapter 6) and are often required in the design stages. The development of chemical models is essentially a complete course in chemical engineering, with practical experience as well, and will not be covered here.



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19 Model-Based Control

Model-based control is based on the concept that if an accurate model of the process can be obtained, a better controller for the process can be designed. This type of control strategy is increasingly used in industry. When a process model is available, processes with long dead time and/or interacting variables can be controlled more effectively.

Model-based control can be a complex topic, especially when applied to multiple loops in a process plant. Keeping to this book's philosophy, we will only outline some of the more fundamental concepts.

Learning Objectives

- Understand the concept of model-based control
- Understand the nature of process dead time
- Review control system design to eliminate unnecessary or unfortunate dead times
- Appreciate the use of predictor algorithms and techniques
- Recognize the benefits of Lambda tuning

19.1 Introduction

In applying feedback control, as discussed previously, no knowledge of the process is required, except for knowing whether the process requires direct or reverse action of the controller. For example, when a proportional-integral-derivative (PID) controller

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receives negative feedback, it can bring the process to the desired value when subjected to set point and demand changes or disturbances.

With detailed knowledge of the process in the form of a mathematical model, a prediction of process behavior to set point and demand changes or disturbances can be computed, and additional controller action can be applied to the process. This provides better control for difficult applications, such as processes with a long dead time, interacting control loops, and control loops with physical or operational constraints.

In previous chapters, we discussed control strategies based on some type of model-based control, such as in feedforward (Chapter 12) and multivariable (Chapter 13) control.

19.2 Dead Time

Dead time is one of the most difficult dynamic characteristics to control. Effectively, we are attempting to control something that has not yet been measured. Not only is it difficult, but the control of dead time also requires complex mathematics to be performed by the controller compared to a standard PID controller.

Dead time was first introduced in Chapter 5. Before discussing the control of dead time, it is helpful to get a sense of its physical outcome. Refer to Figure 19-1, which illustrates a hot-water supply system used to supply water for your morning shower. The arrangement consists of a temperature control system, therefore the installation of a temperature sensor to measure the controlled variable becomes important. The question is where should this sensor be located? It is tempting to install the sensor at the point where the water will be used: at the shower. However, this location will add

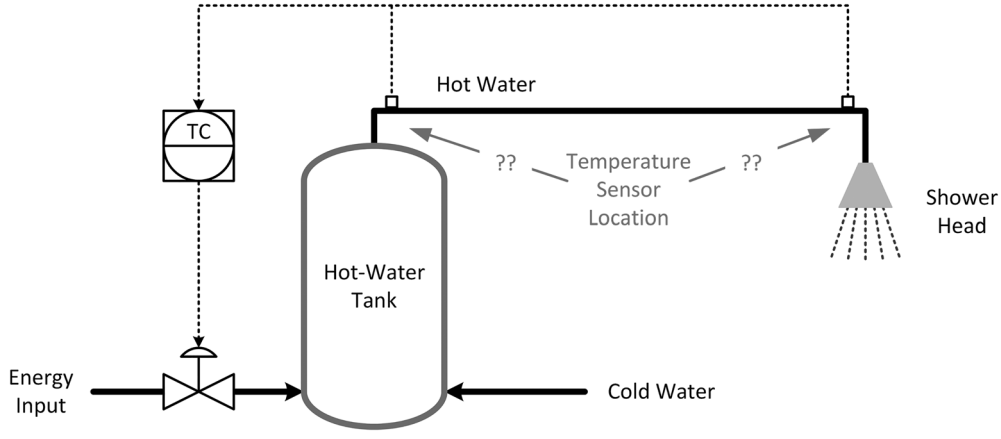


Figure 19-1. Hot-water supply system.

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20 Nonlinear and Adaptive Control

Practically all process control theory is taught in terms of linear systems, whereas all real applications, to some extent, have nonlinear characteristics. There are two basic approaches for dealing with this contradiction

1. either compensate for the nonlinearities, or
2. adapt to them.

We will briefly discuss both in this chapter.

Self-tuning (also called *auto-tuning* or *adaptive tuning*) is a technology that has greatly advanced in recent years. However, the fundamental concepts underlying adaptive control have been around for some time. Practically all proportional-integral-derivative (PID) controllers and control systems today include some type of self-tuning.

Equal-Percentage

- Understand the character and implications of nonlinearities
- Appreciate the use and usefulness of compensation for nonlinearities
- Understand adaptive tuning
- Appreciate general adaptive control concepts

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20.1 Nonlinearity

We saw previously that most, if not all, systems can be described by differential equations (Chapters 6 and 18).

Linear systems are better understood and easier to model and predict. Nonlinear systems are much more difficult to model and predict. When something is said to be linear, we tend to think of a straight line. In other words, solutions to systems that are linear can be extrapolated. Linear differential equations have general solution techniques. But nonlinear differential equations only have specific solution techniques, for specific equations under specific conditions.

A control system is considered linear when it can be described by a linear differential equation. This implies that its performance is predictable. If we change an input by increasing or decreasing it by Δx, allow the system to reach its new steady state, and then again change the input by an additional Δx, the new output will be exactly the same as, and in addition to, the output to the first Δx input. If we reduce the input by Δx, the output will again be the mirror image of the output caused by an increase of Δx in the input. The output is a predictable linear extrapolation of earlier outputs for different amounts of Δx both in extent and shape.

When a control system is nonlinear, its response to a positive change of Δx is different from the mirror image of a response due to a negative change of Δx. The response of the system changes in time and as the load on the system changes. It must be retuned for each change in set point and for different load conditions. However, a linear system may be tuned once and stay tuned for different set points and load conditions. Linear systems behave in a predictable manner.

In general, linear systems have the following characteristics:

- All dependent variables are continuous; that is, they give a continuous response over the range of values exhibited by the system.
- All coefficients of the differential equations that describe the system are constants or functions of time only.
- When several inputs are applied at the same or different locations at the same or a different time, the total response is the sum of the individual responses (superposition).
- The magnitude of the output is directly proportional to the magnitude of the input.

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21 Control System Architecture

This chapter focuses on how individual control loops are assembled into larger control systems. The structure of these larger systems is also illustrated, and some insight into their advantages and disadvantages is provided.

Process control and automated systems have evolved from a simple to an incredibly sophisticated level. To understand the architecture and functional layout of today's process control and automated systems, it is useful to know how they have evolved over time. A brief review of the history will demonstrate how decisions made in the design of early process control systems have impacted today's systems.

Learning Objectives

- Identify the basic hardware components of control loops
- Identify the methods and structure that interconnect components into a control system
- Describe a direct digital control (DDC) system
- Describe a supervisory control and data acquisition (SCADA) system
- Describe a distributed control system (DCS)

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21.1 Basic Components

Most control systems consist of five basic components:

1. Sensors and transmission components
2. Discrete devices
3. Final control elements
4. Controllers
5. Display/recording components

We will discuss each of these briefly in this section. At a minimum, a basic control loop consists of items 1, 3, and 4.

Sensors and Transmission Components

Temperature, flow, pressure, and level are the four major variables measured in process control systems. However, many other variables, such as pH, speed, position, humidity, composition, and so on, may also be measured. The sensors that make these measurements may be simple or very complex. They are connected from their field location to a display, record, and/or control location that may be nearby or remote. The transmitted signal may take many different forms, but 4 to 20 mA and digital transmission over wires, optics, Wi-Fi, or radio are the most established standards. Most variables have their own unique twisted-pair wire connection, but signals may also be multiplexed and/or transmitted via a fieldbus structure.

Many sensors are intrinsically digital, such as on-off devices. The trend for nondigital sensors is toward providing digital output capabilities. Also, many sensors are now being made "smart" with an internal microprocessor, providing a facility for remote or self-calibration and data logging. Digital sensor output can be converted back to analog for transmission on a 4 to 20 mA wire, but there is a loss of accuracy and repeatability.

Discrete Devices

Discrete devices, such as indicators and switches, are a part of practically all control installations. Indicators provide process status and alarm conditions. Switches are used to start up and shut down equipment and also to initiate proper sequencing of batch processes.



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22 Digital Systems

Control methods have evolved from mechanical, pneumatic, and electromechanical systems to electronic and digital control systems. Electronic controls have traditionally been implemented with analog components such as resistors, capacitors, and operational amplifiers. However, with the availability of microprocessors, control systems are now being implemented mostly in digital form. The use of microprocessors in digital control systems has created new opportunities in implementing control strategies, but with them come a need for a new body of knowledge that utilizes these processing capabilities.

This new knowledge is commonly referred to as *digital signal processing* (DSP).

Most, if not all, proportional-integral-derivative (PID) controllers and process models used to control or simulate processes in industry today are microprocessor-based. This chapter will examine how computer computations, models, and simulations are implemented in a typical controller and/or computer.

Understanding the fundamental principles and computational aspect required by the control algorithm will help in the selection and use of the equipment.

Learning Objectives

- Understand the fundamental principles of DSP
- Understand the computational aspect of a process controller
- Convert differential equations to difference equations

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22.1 Hardware Elements

With the performance and reliability inherent to microprocessors and microcontrollers, digital controllers now predominate. In a digital control system, the control processing and calculations are implemented with a microprocessor and/or microcontroller. However, because the actuator commands from the microcontroller are digital, they may have to be converted into analog signals using a digital-to-analog (D/A) converter and low-pass filter. Similarly, the measurements from the sensor are usually analog and will have to be converted into a digital signal using an analog-to-digital (A/D) converter, as well as an anti-aliasing filter and a sample-and-hold (S/H) circuit. The anti-aliasing filter is a low-pass filter that prevents high-frequency signals from entering the A/D converter. The Nyquist[1] criteria state that the sampling frequency of a signal should be greater than twice the maximum frequency of interest. The S/H circuit ensured that the sampled signal does not change during conversion by the A/D converter.

Note that increasingly, measuring instruments and transmitters, as well as actuators, are also microprocessor-based, and many of these devices are capable of providing and receiving signals in digital form.

Figure 22-1 shows a block diagram of a typical digital control system. The D/A converters convert the digital signal output of the microcomputer, $u(n)$, into an analog signal, $u(t)$, and the A/D converter converts the analog signal $u(t)$ into a digital signal, $u(n)$.

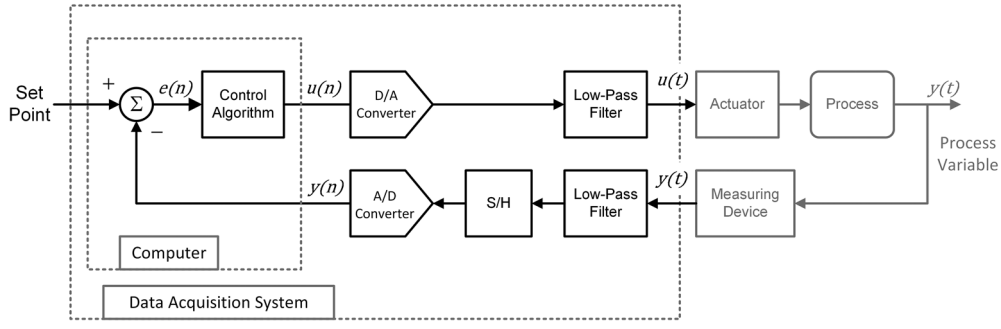


Figure 22-1. Digital control system.

1. Named after Harry Nyquist. Originally from Sweden, Nyquist was an American physicist and electrical and communications engineer who made fundamental theoretical and practical contributions to telecommunications.

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Appendix A: System of Units

Process control involves taking measurements and understanding them. A consistent way of measuring size, mass, level, temperature, time, energy, power, speed, and other parameters requires a consistent system of units.

A consistent system of units consists of fundamental units, which represent base dimensions, and derived units. Most units exist in more than one system of units.

Standards of Measurement

In the process industry, taking accurate measurements is an essential part of process control. A review of units of measurement is in order to ensure we all speak the same language when quantifying our measurements.

Measurements are expressed in both US customary (USC) units (also referred to as *British*, *English*, or *Imperial*) and SI (also referred to as *metric*[1]) units. However, not all USC units are the same as Imperial units. In fact, there can be slight differences among USC units, Imperial units, and English units. The SI units are named after the French Système International d'Unités, or International System of Units. Most scientific work is done using the SI system of units. However, in North America and in the process industry, USC units are still in popular use.

1. There is a technical difference between the SI system and the metric system.

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In the SI system, there are seven base units of measurement: length, mass, time, temperature, electric current, light, and the amount of substance. All other units of measurement are expressed in terms of these fundamental units and are known as *derived units of measurement*.

Length

Length in the SI system is expressed in meters (m).

The USC unit for length is the standard yard, which is equal to 0.914 of the standard meter.

Mass

Mass in the SI system is expressed in kilograms (kg).

The USC unit for mass is the pound. Note that in the English engineering units, the pound-mass and the force are distinct units.

The newton (N) is the SI unit of force; 1 N will give 1 kg of mass a speed of 1 meter per second (m/s). 1 N equals 0.22 lb of force.

For a more detailed explanation, see the "Some Basic Concepts" section at the end of this appendix.

Time

Time is expressed in terms of the second, in all systems of measurement.

Temperature

Temperature is expressed in terms of the kelvin (K). The thermodynamic or kelvin scale of temperature used in the SI system has its origin or zero-point at absolute zero and has a fixed point at the triple point of water, defined as 273.16 K. The Celsius (°C) scale is derived from the kelvin scale. The triple point of water is defined as 0.01°C on the Celsius scale, which is about 32.02°F on the Fahrenheit scale. This applies to all systems.

Note that the Celsius and Fahrenheit scales are denoted in degrees (°), but the kelvin scale is not.

Electric Current

Electric current is expressed in terms of the ampere (A), which is named after André-Marie Ampère, a French mathematician and physicist. This applies to all systems.



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Appendix B: Graphic Symbols for Process Measurement and Control

Process control systems are usually documented using the following four major types of drawings:

1. Block diagrams
2. Process flow diagrams (PFDs)
3. Piping and instrumentation diagrams (P&IDs)
4. Loop diagrams

Block diagrams are primarily used in analysis. PFDs are used preliminary in design and system conception. P&IDs, also commonly referred as *process control instrumentation diagrams* and *process/piping and instrumentation diagrams*, are an important part of understanding process control because they show schematically how all the control components and the process are interconnected. Instrumentation detail varies with the degree of design complexity. Loop diagrams are used in construction and maintenance.

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The basis for the graphical presentation of process control and measurement information is ISA-5.1-2009, *Instrumentation Symbols and Identification*. The material presented in this appendix consists of excerpts from that standard and is used with permission. For full detail, however, the ISA standard should be consulted.

The standard defines how each symbol is constructed using graphical elements, alpha and numeric identification codes, abbreviations, function blocks, and connecting lines.

Figure B-1 shows a typical detailed P&ID diagram.

Deciphering the Symbols

ISA-5.1 defines four graphical elements.

1. Discrete instrument
2. Computer system and software
3. Alternative or safety instrumented system
4. Primary choice or basic process control system

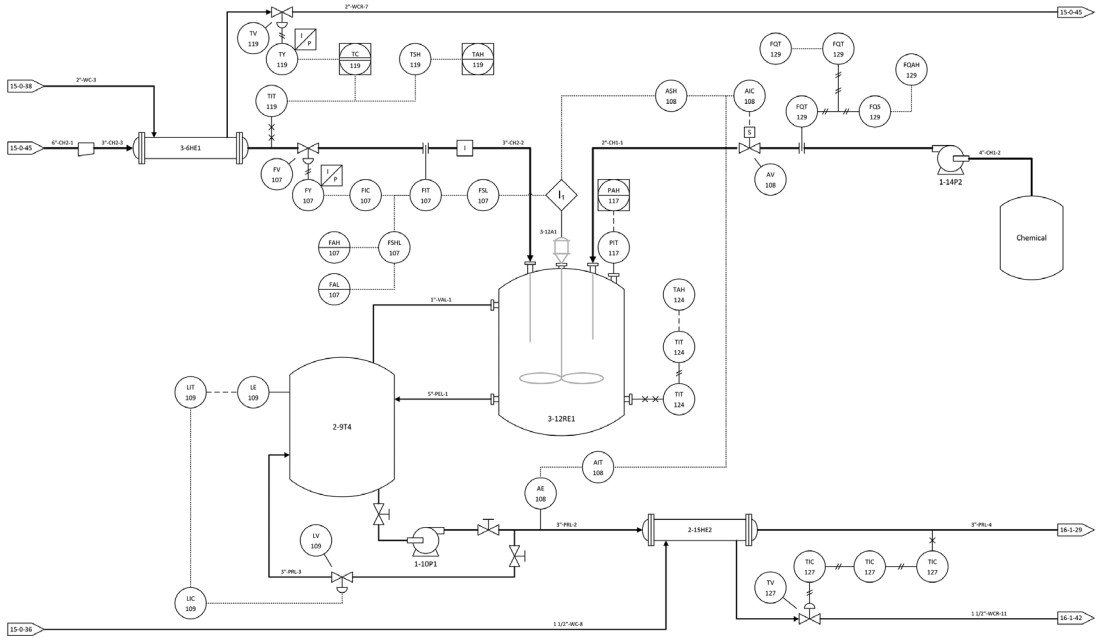


Figure B-1. Typical detailed P&ID.

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Appendix C: The Laplace Transform

Introduction

The Laplace transform was developed early in the nineteenth century by a French mathematician and astronomer named Pierre Simon de Laplace. It was originally strictly a mathematical exercise and was not applied to the field of electronic and control technology until the twentieth century. Chapters 6 and 18 explained that components and systems can be expressed using differential equations.

Solving differential equations can be complex and time-consuming. The Laplace transform enables us to transform these differential equations into simpler algebraic equations. Then by solving the algebraic equation, we can obtain system and control component transfer functions. With the obtained transfer functions, we can then compute the system or component's response to inputs. In other words, the Laplace transform is a mathematical model that describes systems in time and frequency response.

Frequency response, although not as intuitive as time response, should be familiar to anyone who has used the equalizer on a home stereo or computer. The equalizer display indicates the frequency distribution and magnitude of sound.

The Laplace transform takes us from a domain called the *time domain* to another domain called the *frequency domain.* In the time domain, the signal is given or determined for

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each instant of time. We say that the input and output signals are functions of time, and we append a (t) to the function name to indicate that time is the independent variable.

The time-domain equation of a component defines its output as a function of time and the input signal.

In the frequency domain, the magnitude and the phase angle of the signal are given or determined for each value of a frequency usually designated by the letter s, where s has the units of 1/s or s^{-1}. We say that the input and output signals are functions of frequency and append an (s) to the variable name to indicate that frequency is the independent variable. The frequency-domain equation of a component defines the magnitude and phase angle of the output signal as a function of both frequency and the input signal.

We use the Laplace transform to obtain the frequency-domain equation from the time-domain equation.

Lowercase letters are used to represent signals in the time domain, and uppercase letters are used for signals in the frequency domain.

Although deriving the Laplace transforms of functions gives us a better understanding of what is taking place, it is not necessary to apply the Laplace transform in automation analysis. The derivations provided at the end of this appendix are for demonstration only. The reader is by no means required to be able to demonstrate this type of mathematical competency.

The Laplace transform designated by the letter L is given by the following integral:

$$F(s) = L[f(t)] = \int_0^\infty f(t)e^{-st}dt \tag{C-1}$$

where

$F(s)$ = the Laplace transform of $f(t)$
t = time
s = a complex number of the form $a + j\omega$
and $j = \sqrt{-1}$

This equation represents the Laplace transform of a time function $f(t)$[1].

1. Some textbooks use the letter p instead of s. In that case, it is referred to as the *Heaviside operator.*



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Appendix D: Exercise Solutions

Chapter 2: Basic Control Concepts

2.1 Consider an electric oven in a typical modern kitchen. Identify the controlled variable (CV), the manipulated variable, and the disturbances.

Answers:

Controlled variable: oven temperature

Manipulated variable: electric current

Disturbances: ambient temperature, oven contents, endothermic and exothermic reactions leaks, door opening and closing

2.2 Consider an automatic, gas-fired, home hot-water tank. Identify the controlled variable, the manipulated variable, and the disturbances.

Answers:

Controlled variable: water temperature

Manipulated variable: gas flow

Disturbances: water usage, Btu content of gas, ambient temperature, inlet water temperature

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2.3 Imagine you own a backyard swimming pool. Describe a manual control system to measure the pH of the pool water and to add an acidic solution to adjust the pH. Define the controlled variable, the manipulated variable, and the disturbances.

Answers:

Manual system:

1. Take a sample of the pool water.
2. Use litmus paper or an equivalent to measure the pH.
3. Add acidic solution as necessary.

For this manual system:

Controlled variable: pool water pH

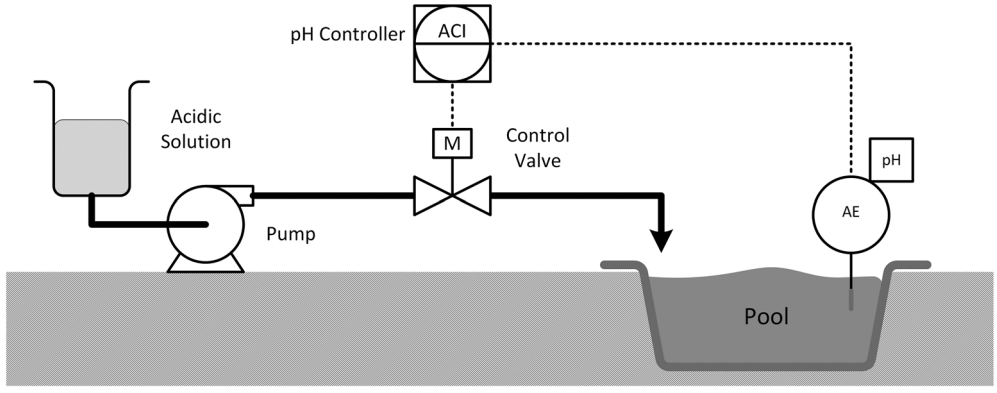
Manipulated variable: acidic solution added

Disturbances: variation in strength of acidic solution, evaporation rate, pH of any makeup water added to pool

2.4 Describe how to automate the control of your swimming pool. Assume you have a tank of acid solution to pump into your pool to control pH; use feedback control.

Answers:

A feedback automatic control system might appear as follows:



2.5 The cruise control feature used to control speed in an automobile is a good example of feedback control. Outline its operation in terms of feedback control.

Answers:

Set point: desired speed

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