PRINCIPLES AND PRACTICE OF AUTOMATIC PROCESS CONTROL

Carlos A. Smith

Armando B. Corripio

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Carlos A. Smith
University of South Florida

Armando B. Corripio
Louisiana State University

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This work is dedicated with all our love to

The Smiths:

Cristina, Cristina M.,
Carlos A., Jr., and
Mr. and Mrs. Rene M. Smith

The Corripios:

Connie, Bernie, Mary, Michael,
and Consuelo

and to our dearest homeland, Cuba

PREFACE

A most important objective of this book is to present the practice of automatic process control along with the fundamental principles of control theory. To this end we have included in the book a generous number of case studies, problems, and examples taken directly from our experience as industrial practitioners and consultants. It is our belief that, although there are many fine books in the market that cover the principles and theory of automatic process control, most of them do not expose the reader to the practice of these principles.

The notes from which the book was developed have been tested during the last few years in senior-level chemical and mechanical engineering courses at the University of South Florida and Louisiana State University. Also, many parts of the book have been used for the past several years by the authors in teaching short courses to practicing engineers in this country and abroad.

The import of the book is directed toward the process industries. The book can be used by senior engineering students, principally in the fields of chemical, mechanical, metallurgical, petroleum, and environmental engineering, and by technical personnel in the process industries. We believe that in order to control a process, the engineer must first understand the process. This is why throughout this book we base the understanding of process dynamic response on the principles of material and energy balances, fluid flow, heat transfer, separation processes, and reaction kinetics. Most senior engineering students will have the background necessary to understanding these concepts at the level at which we present them. The mathematical level required is covered in any undergraduate engineering curriculum—mainly operational calculus and differential equations.

The definitions of terms and mathematical tools used in the study of process control systems are presented in Chapters 1 and 2. Chapters 3 and 4 present the principles of process dynamic response. In these chapters we use numerous examples to show how to develop simple process models and to learn the physical significance of the parameters that describe the dynamic behavior of the process.

Chapter 5 presents a discussion of some important components of a control system. Namely, sensors, transmitters, control valves, and feedback controllers. The practical operating principles of some common sensors, transmitters, and control valves are presented in Appendix C. Students who are interested in acquiring a working knowledge of process instrumentation are strongly encouraged to study Appendix C.

The design and analysis of feedback control systems is the subject of Chapters 6 and 7, while the rest of the important industrial control techniques are treated in Chapter 8. These are ratio, cascade, feedforward, override, selective, and multivariable control. We use numerous practical examples to illustrate actual industrial applications of these techniques.

The principles of mathematical modeling and computer simulation of processes and their control systems are presented in Chapter 9. In this chapter we present a very useful modular program architecture that can be used to illustrate the principles of dynamic response, stability, and tuning of control systems.

In our experience, a one-semester course should include the first six chapters of the book through Section 6-3, plus the section on feedforward control from Chapter 8. Then, depending upon the availability of time and the instructor's preference, the sections on computing relays, ratio control, cascade control, root locus, and frequency response can be included. These sections are independent of each other. If the course includes a laboratory, the material in Chapter 5 and Appendix C should serve as excellent background for the laboratory experiments. The examples in Chapter 9 can serve as blueprints for computer simulation "experiments" to supplement the actual laboratory experiments.

If two semesters or quarters are available for teaching the course, the entire text can be presented in detail. The course should include a term project using the process control problems of Appendix B. These are actual industrial problems and provide the student with the opportunity to design, from scratch, the control system for a process. We strongly believe that these problems are an important contribution of this book.

In this book we have exclusively used the transfer function approach over the state variable approach for three reasons: First, we strongly believe that transfer functions are more viable for conveying understanding of process control concepts; second, we are not aware of any control schemes used in industry today that require the state variable approach in their design; and finally, the state variable approach requires a stronger mathematical background than transfer functions.

In any work of this type there are numerous people who contribute, encourage, and help the authors in different ways. We are no exception and feel blessed to have these persons around. From industry, both authors would like to thank Charles E. Jones of Dow Chemical USA, Louisiana Division, for supplying the motivation of the industrial practice of process control and for his encouraging us to seek higher education. From academia, our two universities have provided the atmosphere and help necessary for completing this project. We would like to thank the faculty and students of our departments for developing in us a deep appreciation and satisfaction in academic instruction. To serve as agents in the training and development of young minds is certainly a most rewarding profession.

The encouragement of our undergraduate and graduate students (the young minds) will never be forgotten, especially that of Tom M. Brookins, Vanessa Austin, Sterling L. Jordan, Dave Foster, Hank Brittain, Ralph Stagner, Karen Klingman, Jake Martin, Dick Balhoff, Terrell Touchstone, John Usher, Shao-yu Lin, and A. (Jefe) Rovira. From the University of South Florida, Carlos A. Smith would like to thank Dr. L. A. Scott; his friendship and advice during the last ten years have been most helpful. Thanks are also due to Dr. J. C. Busot; his constant question, "When are you going to finish the book?" has certainly helped in providing some of the fuel necessary to continue. From Louisiana State University, Armando B. Corripio would like to acknowledge the role Drs. Paul W. Murrill and Cecil L. Smith played in getting him started in automatic process control. They not only taught him the theory, they instilled in him their love for the subject and for teaching it.

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Carlos A. Smith
Tampa, Florida

Armando B. Corripio
Baton Rouge, Louisiana
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CONTENTS

CHAPTER
1
Introduction

The principal purpose of this chapter is to present you, the reader, with the need for automatic process control and to motivate you to study it. Automatic process control is concerned with maintaining process variables, temperatures, pressures, flows, compositions, and the like at some desired operating value. As we shall see in the ensuing pages, processes are dynamic in nature. Changes are always occurring, and if actions are not taken, the important process variables—those related to safety, product quality, and production rates—will not achieve design conditions.

This chapter also introduces two control systems, takes a look at some of their components, and defines some terms used in the field of process control. Finally, the background needed for the study of process control is discussed.

1-1. A PROCESS CONTROL SYSTEM

In order to fix ideas, let us consider a heat exchanger in which a process stream is heated by condensing steam. The process is sketched in Fig. 1-1.

The purpose of this unit is to heat the process fluid from some inlet tempertature $T_i(t)$, up to a certain desired outlet temperature, $T(t)$. As mentioned, the heating medium is condensing steam. The energy gained by the process fluid is equal to the heat released by the steam, provided there are no heat losses to the surroundings, that is, the heat

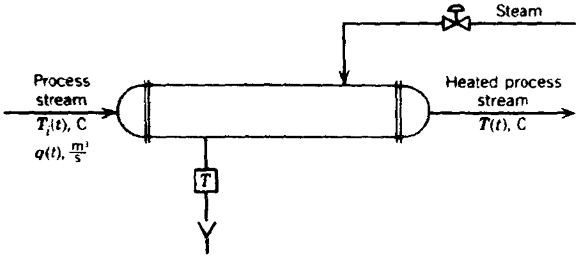

Figure 1-1. Heat exchanger.

exchanger and piping are well insulated. In this case the heat released is the latent heat of condensation of the steam.

In this process there are many variables that can change, causing the outlet temperature to deviate from its desired value. If this happens some action must be taken to correct for this deviation. That is, the objective is to control the outlet process temperature to maintain its desired value.

One way to accomplish this objective is by first measuring the temperature $T(t)$, then comparing it to its desired value, and, based on this comparison, deciding what to do to correct for any deviation. The flow of steam can be used to correct for the deviation. That is, if the temperature is above its desired value, then the steam valve can be throttled back to cut the steam flow (energy) to the heat exchanger. If the temperature is below its desired value, then the steam valve could be opened some more to increase the steam flow (energy) to the exchanger. All of this can be done manually by the operator, and since the procedure is fairly straightforward, it should present no problem. However, since in most process plants there are hundreds of variables that must be maintained at some desired value, this correction procedure would require a tremendous number of operators. Consequently, we would like to accomplish this control automatically. That is, we want to have instruments that control the variables without requiring intervention from the operator. This is what we mean by *automatic process control.*

To accomplish this objective a *control system* must be designed and implemented. A possible control system and its basic components are shown in Fig. 1-2. (Appendix A presents the symbols and identifications for different instruments.) The first thing to do is to measure the outlet temperature of the process stream. This is done by a *sensor* (thermocouple, resistance temperature device, filled system thermometers, thermistors, etc.). This sensor is connected physically to a *transmitter*, which takes the output from the sensor and converts it to a signal strong enough to be transmitted to a *controller*. The controller then receives the signal, which is related to the temperature, and compares it with the desired value. Depending on this comparison, the controller decides what to do to maintain the temperature at its desired value. Based on this decision, the controller then sends another signal to the *final control element*, which in turn manipulates the steam flow.

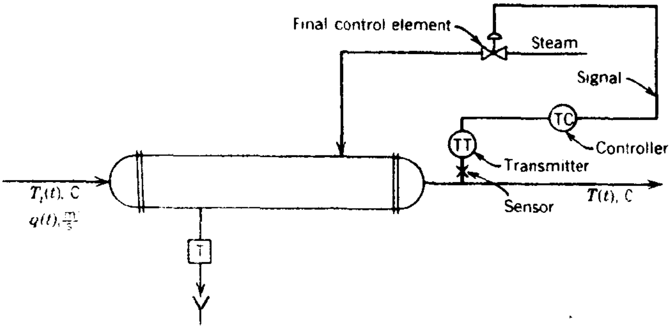

Figure 1-2. Heat exchanger control system.

The preceding paragraph presents the four basic components of all control systems. They are

1. *Sensor*, also often called the primary element.
2. *Transmitter*, also called the secondary element.
3. *Controller*, the "brain" of the control system.
4. *Final control element*, often a control valve but not always. Other common final control elements are variable speed pumps, conveyors, and electric motors.

The importance of these components is that they perform the three basic operations that *must* be present in *every* control system. These operations are

1. *Measurement (M):* Measuring the variable to be controlled is usually done by the combination of sensor and transmitter.
2. *Decision (D):* Based on the measurement, the controller must then decide what to do to maintain the variable at its desired value.
3. *Action (A):* As a result of the controller's decision, the system must then take an action. This is usually accomplished by the final control element.

As mentioned, these three operations, M, D, and A, *must* be present in *every* control system. The decision-making operation in some systems is rather simple, while in others it is more complex; we will look at many of them in this book. The engineer designing a control system must be sure that the action taken affects the variable to be controlled, that is, that the action taken affects the measured value. Otherwise, the system is not controlling and will probably do more harm than good.

1-2. IMPORTANT TERMS AND OBJECTIVE OF AUTOMATIC PROCESS CONTROL

At this time it is necessary to define some terms used in the field of automatic process control. The first term is *controlled variable*. This is the variable that must be maintained or controlled at some desired value. In the preceding example, the process outlet temperature, $T(t)$, is the controlled variable. The second term is *set point*, the desired value of the controlled variable. The *manipulated variable* is the variable used to maintain the controlled variable at its set point. In the example, the flow of steam is the manipulated variable. Finally, any variable that can cause the controlled variable to deviate away from set point is defined as a *disturbance or upset*. In most processes there are a number of different disturbances. As an example, in the heat exchanger shown in Fig. 1-2, possible disturbances are the inlet process temperature, $T_i(t)$, the process flow, $q(t)$, the quality of the energy of the steam, ambient conditions, process fluid composition, fouling, and so on. What is important here is to understand that in the process industries, most often it is because of these disturbances that automatic process control is needed. If there were no disturbances, design operating conditions would prevail and there would be no necessity of continuously "policing" the process.

The following additional terms are also important. *Open-loop* refers to the condition in which the controller is disconnected from the process. That is, the controller is not making the decision of how to maintain the controlled variable at set point. Another instance in which open-loop control exists is when the action (A) taken by the controller does not affect the measurement (M). This is indeed a major flaw in the control system design. *Closed-loop control* refers to the condition in which the controller is connected to the process, comparing the set point to the controlled variable and determining corrective action.

With these terms defined, the objective of an automatic process control system can be stated as follows:

> The objective of an automatic process control system is to use the manipulated variable to maintain the controlled variable at its set point in spite of disturbances.

1-3. REGULATORY AND SERVO CONTROL

In some processes the controlled variable deviates from a constant set point because of disturbances. *Regulatory control* refers to systems designed to compensate for these disturbances. In some other instances the most important disturbance is the set point itself. That is, the set point may be changed as a function of time (typical of this are batch processes), and therefore the controlled variable must follow the set point. *Servo control* refers to control systems designed for this purpose.

Regulatory control is by far more common than servo control in the process industries. However, the basic approach to designing either of them is essentially the same. Thus, the principles learned in this book apply to both cases.

1-4. TRANSMISSION SIGNALS

Let us now say a few words about the signals used to provide communication between instruments of a control system. There are three principal types of signals in use in the process industry today. The *pneumatic signal*, or air pressure, ranges normally between 3 and 15 psig. Less often, signals of 6 to 30 psig or 3 to 27 psig are used. The usual representation in piping and instrument diagrams (P&ID) for pneumatic signals is -//——//-. The *electrical*, or *electronic, signal* ranges normally between 4 and 20 mA. Less often 10 to 50 mA, 1 to 5 V or 0 to 10 V are used. The usual representation in P&ID's for this signal is --------. The third type of signal, which is becoming common, is the *digital*, or *discrete*, *signal* (zeros and ones). The use of process-control systems based on large-scale computers, minicomputers, or microprocessors is forcing increased use of this type of signal.

It is often necessary to change one type of signal into another type. This is done by a *transducer*. For example, there may be a need to change from an electrical signal, mA, to a pneumatic signal, psig. This is done by the use of a current (I) to pneumatic (P) transducer (I/P). This is shown graphically in Fig. 1-3. The input signal may be 4 to 20 mA and the output 3 to 15 psig. There are many other types of transducers: pneumatic-to-current (P/I), voltage-to-pneumatic (E/P), pneumatic-to-voltage (P/E), and so on.