Process Measurement and Control

Introduction to Sensors, Communication, Adjustment, and Control

Roy E. Fraser

PROCESS MEASUREMENT AND CONTROL

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Olgai, manai mīļai dzīvesbiedrei

And to our wonderful family

Martin, Jane, and children
Laura, Valerie, and Melinda

Natalie, David, and children
Daniel, Erin, and Tessa

PREFACE

This book is a text for students learning automatic control systems and a reference for those pursuing careers in industry. When readers select a measuring sensor or a control valve, this book will refresh them about the important details that must be considered. When they interconnect the sensor and control valve into a communicating network, this book will remind them of the important methods for minimizing interference from electrical and magnetic fields. When they tune a controller, it will guide them toward establishing a desirable control loop response to a disturbance.

The concepts discussed in this book focus on a classic process control loop with its four major blocks: the measuring sensor block, the controller block, the process adjustment block, and the process block. Design procedures include the selection of measuring sensors and control valves. The sensors concentrate on the measurement of temperature, pressure, flow rate, and level, and analysis of humidity and electrolytic conductivity. Also covered is the design of network wiring to minimize interference.

Operational procedures show the presentation of process information for safely monitoring the trajectory of a changing process (e.g., trend display and alarm status), and they describe control loop responses to disturbances. The financial investment in this kind of equipment is also reviewed.

Maintenance procedures emphasize calibration of measuring sensors. Maintenance of a network to minimize interference from inadvertent grounds on the network is also described. Additionally, the tuning of controllers to achieve a desirable response to disturbances is emphasized.

Each chapter begins with objectives that present the concepts covered. At the end of each chapter are sets of questions and problems, suggested practical lab assignments, and references that provide additional resources on the concepts covered in this book. Selected problems have answers in Appendix C.

Chapter 1 introduces continuous automatic control and differentiates it conceptually from discrete control. The control loop is emphasized as the basic concept for continuous control of a process variable. The four blocks of every control loop are described, and their input and output signals are shown on a block diagram. The Instrument Society of America symbols are presented for describing control systems on a Process and Instrument Diagram (P&ID).

Chapter 2 begins with instrument calibration concepts and documents. Instruments for sensing temperature, pressure, flow, level, humidity, and electrolytic conductivity are described, and many of the device limitations for these measurements are mentioned. These limitations are shown as important elements involved in the selection of a device for a successful application.

The presentation of process control information for human operators and for machines is introduced in Chapter 3. The overview display, process group display, and the point display are described. Additional displays include trend, alarm summary, and hourly averages.

Chapter 4 presents techniques to achieve reliable, secure data communications around the control loop. Comparison of pneumatic and electric communications are made to show the speed of the electrical technique and its potential hazards. Problems due to interference from magnetic and electric fields and from improper electrical grounding are described, along with proper techniques to minimize these problems. The concepts of networks are introduced.

Chapter 5 emphasizes the application of control valves for process adjustment. The sizing of control valves for liquid and gas flow adjustment follows ISA standard S75.01.

Chapter 6 introduces the proportional, integral, and derivative (PID) controller and explains its functions and the ultimate cycle method for its tuning. Ratio control and cascade control of a process are also explained.

The appendixes describe ISA symbols, display blank calibration documents, display photos of control valves, list answers to selected problems, list ASCII symbols and codes, describe calculations for liquid pressure drops in piping, and list a table of thermocouple millivolts versus temperature and a table of RTD resistance versus temperature.

Students and instructors should review the Study Procedures on page vii to assess whether they have the prior training required to rapidly absorb the information in this book. The estimated time required for students to learn the material, study the theory, answer questions and problems, and perform the assignments is also given. The instructor's manual available for use with this text provides an outline of study and further information on how to successfully teach classes in process measurement and control.

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STUDY PROCEDURES

This book is designed for students planning careers as measurement and control technicians, technologists, and engineers. At a minimum, such students should have had mathematics background, including algebra, trigonometry, plane geometry, and complex variables. They should also have studied electricity and electronics to the point where they can analyze circuits for current, voltage drops, and impedances, and can use ammeters, voltmeters, and oscilloscopes to troubleshoot a circuit. A basic expertise in using computer spreadsheets, word processors, and CAD programs is also required.

This book is intended for a structured lecture program, but it may also be used in an individualized-learning program with equipment for lab assignments. The lab assignment demonstrates to the student the concepts described in the lesson and is closely related to the industrial application of those concepts.

To completely learn the material in this book, the student needs to invest approximately two lecture hours, two lab assignment hours, and two to four home hours—to study before the lecture, to do the problems after the lecture, and to prepare for the lab assignment and report—each week during a 16-week semester. A recommended lab assignment report format is shown below. About 30 hours are required in the classroom, 30 hours in the lab, plus another 60–70 hours study time.

Project or Lab Assignment Report Format

Concise, complete reports demonstrate an understanding of the material in the section being studied. The following format will help ensure such reports are produced.

Title Page

- Course name and number
- Assignment number and title
- Instructor's name
- Date assignment was performed
- Student's name
- Partner's name

Subsequent Pages

Objective	Include a copy of the stated objective.
Procedure	Include a copy of the requested procedure to follow.
Diagrams	Show how you actually connected the equipment.
Data	List the data that you collect.
Results	Describe your actual results and compare them to expected results. Describe any unexpected results.
Conclusions	Answer any questions. Try to give reasons for unexpected results.

An effective report will help the student better understand the subject matter, and it will serve as a reference for further work. The report should be started while preparing for or while performing the assignment. The student should have the instructor assess it, initial completed sections, and then mark it within one or, at most, two weeks of the assignment period. Excessive neatness is not essential (simply cross out any incorrect or unnecessary sections). However, the student should keep and organize all the completed reports in a single binder as he or she proceeds through the course.

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1

INTRODUCTION TO PROCESS MEASUREMENT AND CONTROL

OBJECTIVES

When you complete this chapter you will be able to:

- Define process measurement
- Define process control
- Calculate simple return on investment from a process control system
- Sketch a block diagram of a process control loop
- Describe typical industrial processes under process control
- Draw simple Process and Instrumentation Diagrams (P&ID) using ISA symbols
- Describe the measuring sensor block of a control loop
- Describe the controller block of a control loop
- Describe the process adjustment block of a control loop
- Describe the signals circulating around a control loop

1.1 PROCESS MEASUREMENT AND CONTROL DEFINED

Processes include anything from the heating of your house to the marketing of baby food. For our purposes, however, we will be concerned only with industrial processes such as the distillation of crude oil, or the digestion of wood chips to make pulp, or the conversion of pulp to paper, or the fabrication of plastic products such as 1-liter plastic soft drink bottles. These are overall processes and each of them will usually include many subprocesses.

Process measurement is defined as the systematic collection of numeric values of the variables that characterize a process to the extent that the process control criteria of the process user are satisfied. As an example, if you require your house temperature to be maintained between 18°C and 24°C with an accuracy of 0.25°C, then your thermostat must measure the temperature and collect its numeric value for your furnace controller so that it will maintain this accuracy. As another example, if the owner of a distillation plant making gasoline requires a certain octane range from the plant, then all the measuring and control instruments on the plant must be chosen to work together accurately to ensure that the plant achieves those criteria. As a final example, if the manufacturer of baby food wishes to make mashed carrots for the market, then he will ask a market analyst to acquire data on the potential customers of mashed carrots for babies.

The purpose of process measurement is to assist a human or a machine to monitor the status of a process as it remains at some steady state or as it changes from one state to another such as heating up crude oil. In most cases the human or machine will guide or force the process to change safely from an initial state to a more desirable state (e.g., forming a plastic bottle). This is process control.

1.2 INVESTMENT

Of course, the purpose of any process equipment and its measurement and control system is to provide a satisfactory return on its invested capital. The best control system maximizes the return on the whole process plant, not just on the capital invested in the control system. It does this over its lifetime. Therefore, maintenance costs and loss of production costs due to breakdowns should be considered when selecting the measurement and control system. Reliability is a very important aspect in the selection of systems and often worth the added initial costs. Reliability of the system is in itself important. So is the reliability of the system supplier to provide replacement parts and service in the future.

An example of justifying the expenditure of $2,353,000 on a replacement control system for an existing process, using an old, manual method of control, has the following simple, estimated costs:

Annual losses from old control system	
Old system losses due to off-spec product	$850,000
Old system losses due to control system downtime	145,000
	$995,000
Annual savings from new control system	
New system losses due to off-spec product	$250,000
New system losses due to control system downtime	145,000
	$395,000
Reduction of losses due to new system	$600,000
Extra annual operating and maintenance cost of new system	115,000
Annual savings from new system	$485,000

One-time costs of new system	
Lowest price vendor's price	\$1,875,000
Spare parts costs	125,000
Installation costs	265,000
Training costs for plant personnel	88,000
	\$2,353,000

$$\text{Expected return on investment} = \frac{\$485,000/\text{yr} \times 100\%}{\$2,353,000} = 20.6\%/\text{yr}$$

$$\text{Payback period} = \frac{\$2,353,000}{\$485,000/\text{yr}} = 4.85 \text{ years}$$

This example shows in a simple way the method of comparing engineering projects in order to select the ones that will make the most profit for the company planning to make improvements to its plant. For example, if the company has many possible projects to invest its money in, it will choose to rank them according to their return on investment. The ones with a high return on investment will usually be chosen over the ones with low return on investment.

1.3 CONTINUOUS AND DISCRETE PROCESS CONTROL LOOPS

There are two main forms of process control: continuous and discrete (or on/off). The continuous form of process control implies smooth even measurement of the process variable over a fairly wide range that is finely resolved into many hundreds or thousands of values. For example, the temperature in your home may cover a continuous range of 0°C to 40°C resolved into at least 256 values, or spacings of 0.156°C. The discrete form of process control implies a discrete variable with only a few (at least two, such as on and off) status points covering its range. For example, an electric motor may be stopped (off) or running (on). This book concentrates on continuous control.

Continuous process control emphasizes feedback using a closed loop. Figure 1.1 shows a typical closed loop. An example of a closed loop is cruise control on an automobile. The driver sets a certain desired speed as the set-point signal and places the car on cruise control. If the feedback signal (speed of the car) is less than the set-point signal, and a positive error (difference between set-point speed and feedback speed) exists, then the controller increases its output signal. The output signal opens the throttle (the process adjusting device) of the engine (the process), causing the car to speed up. The speed sensor detects this increase in speed (the measured process variable) and sends a stronger feedback signal to the controller. This action continues until the feedback signal equals the set-point signal, and then the controller output signal maintains its value, keeping the car at the desired speed.

Discrete process control emphasizes Boolean logic using gates and timers. Figure 1.2 shows a generalized logic diagram. An example of discrete process control is

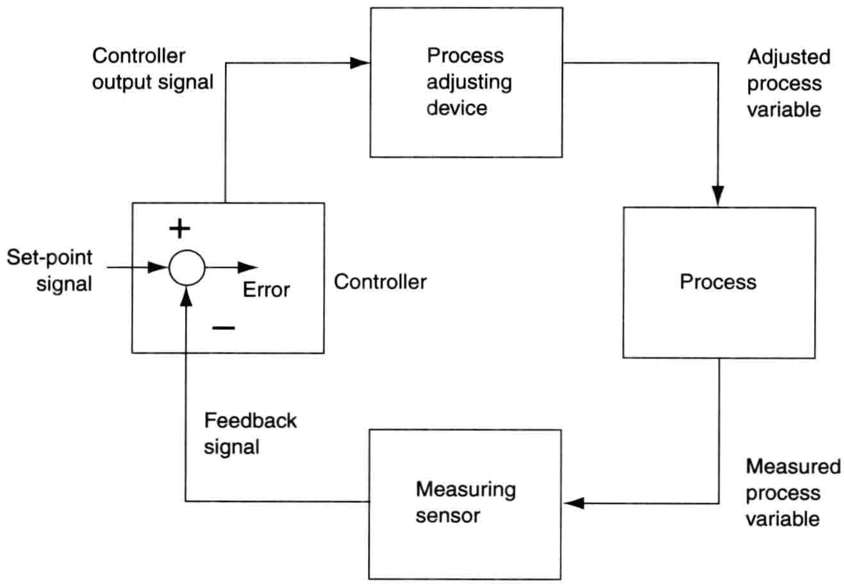

FIGURE 1.1
Typical closed loop for continuous process control

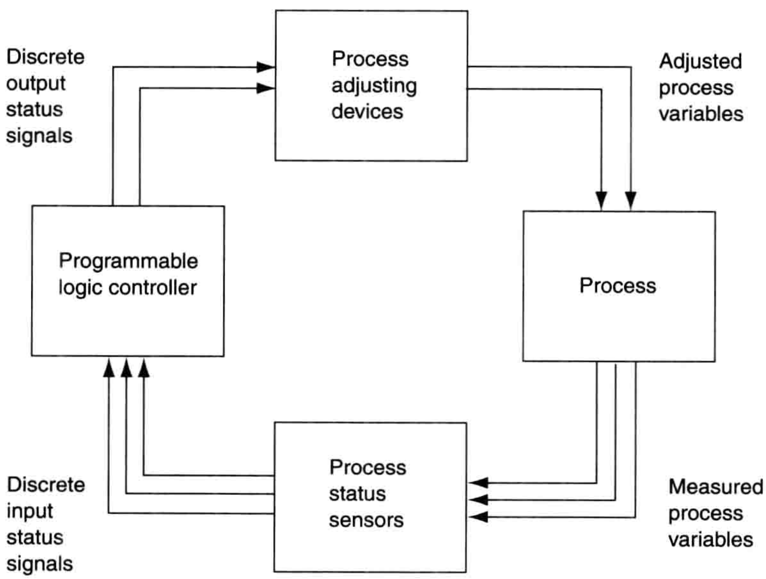

FIGURE 1.2
Generalized logic diagram for discrete process control

the control of a crossing gate at a railroad crossing. Two train sensors are used on the railway tracks. One is placed on the tracks at one side of the crossing and the other on the tracks on the other side of the crossing. If either sensor detects a train, the crossing gate on the highway should close. However, if a short train appears it may be between the sensors and the crossing gate may open at an incorrect time. The control logic should not let this happen; it should only allow the gate to open after the train passes over the second sensor. In this case the process is the flow of traffic over the highway and over the railway. The railway train sensors are the process status sensors, and they produce the discrete input status signals for the programmable logic controller. Based on these signals, the programmable logic controller decides when to change the discrete output status signal. This signal operates the motor (process adjusting device) driving the gate open or closed.

1.4 THE PROCESS BLOCK OF A CONTROL LOOP

Figure 1.1 is a most important figure. The four blocks and the signals that connect them together will be referred to frequently. The most important block is the process block because it dictates how the other blocks are expected to perform. The measuring sensor must be selected to measure the process variable that is associated with the process. The process adjusting device must be selected to adjust the adjusted—or manipulated—process variable that is associated with the process.

The adjusted or manipulated variable adjusts the process so that the measured process variable approaches more closely to the set-point value. For example, in an automobile on cruise control, the throttle position is the adjusted process variable, and it adjusts the fuel flowing to the engine. As the fuel flow is increased, the speed of the auto increases. The speed of the auto is the measured process variable, and if the control system is functioning correctly, the speed should be approaching more closely to the set-point value.

In order to describe control loops, ISA symbols (described in Appendix A) have been used by many large industrial companies for more than 50 years. Each instrument or instrument function is identified with a circle (or "balloon"), some letters, and a number as its symbol. Most of the letters are defined by ISA, but some may be defined by the user. The process symbol is not usually defined by ISA and here the user may be creative. Every control loop has hardware or software that is represented by the four blocks shown in Figure 1.1. For each loop a process and instrumentation diagram (P&ID) is prepared. For example, as shown in Figure 1.3, there are usually many loops shown on one large diagram for a major process. Each loop on the P&ID uses ISA symbols to show the particular devices that perform the functions shown in Figure 1.1. Figure 1.3 shows a typical liquid flow control loop (F-212) supplying liquid from a pipe to a tank. Figure 1.3 also shows a typical liquid level control loop (L-141) adjusting the flow out of the tank to maintain the tank level at the set point of the level controller (LIC-141). By studying Appendix A you should be able to conclude that the letters and numbers associated with each ISA symbol represent the following: